ASTRONOMY
What Fuels Bizarre Stellar Explosions?

ENVIRONMENT
Looming Security Threat: Climate Change

HEALTH
The Fog of Agent Orange

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Rise of the Mammals

Our ancestors began to flourish long before dinosaurs died out

SPECIAL REPORT

AI

How Brainy Networks Will Remake Our World

JUNE 2016

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SCIENTIFIC AMERICAN

ON THE COVER

Early mammal *Volaticotherium* is known from a fossil from China dating to around 160 million years ago. The fossil preserves an impression of a membrane that stretched between the arm and leg, which would have allowed the animal to glide from branch to branch like a modern-day flying squirrel. *Volaticotherium* is one of a number of species that show that mammals diversified to a surprising degree long before the dinosaurs died out. **Image by James Gurney.**

COURTESY OF NASA/CXC/SAO/F. SEWARD *(composite)*; COURTESY OF NASA/ESA/ASU/J. HESTER AND A. LOLL *(optical)*; NASA/JPL-CALTECH/UNIVERSITY OF MINNESOTA/R. GEHRZ *(infrared)*

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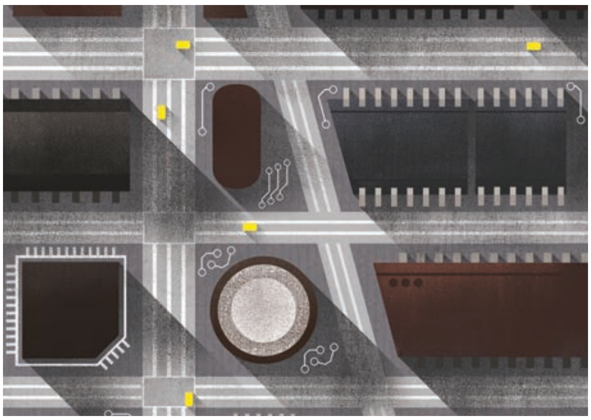

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ON THE WEB

Special Report on Zika
As the Zika virus continues to spread, *Scientific American* explores efforts to contain the threat and develop an arsenal to defend against it.
Go to www.ScientificAmerican.com/jun2016/zika

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FROM THE EDITOR

Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

A Success Story

Talk about humble beginnings. Most of our notions about our mammal ancestors portray them as shrewlike critters barely eking out an existence in the shadow of dinosaurs for millions of years. When the hulking giants got felled in the aftermath of environmental changes from a giant meteor impact, the pathetic warm-blooded runts finally got to make their move, eventually blossoming into the wide diversity of successful species we see today, including humans.

Not so fast. As paleontologists Stephen Brusatte and Zhe-Xi Luo write in this issue's cover story, "Ascent of the Mammals," a series of spectacular recent fossil discoveries reveal surprising twists on the old tales you learned in your schoolbooks. Millions of years before it was ever thought possible, evolution began to lay the groundwork for mammals to become the world's dominant vertebrate species.

CASTOROCAUDA **shows mammalian adaptability to new niches in this early cover sketch.**

The tiny animals developed an array of specializations and evolutionary innovations, making them adept at taking advantage of a variety of ecosystem niches. Their tooth shapes enabled the processing of new foods, and their growth patterns enhanced survival of their young. Early mammals came to climb, to glide, to swim. Ultimately, as we know, they crawled all over this blue planet. Turn to page 28 to find out how.

Delve Deeper

The process of science has many admirable traits, and one of them is how it builds on prior knowledge—which is ideally freely shared. For that reason, a little over a year ago *Scientific American*'s parent company began an experiment of its own: through the use of software from ReadCube, supported by the company Digital Science, it enabled readers of this magazine and about 100 other mass-market publications free access to view original research papers published in close to 50 journals, including *Nature.* Readers who clicked on links placed in articles at ScientificAmerican.com and elsewhere could follow their curiosity, delving deeper into the methods and results of published findings. Each paper received an average of 200 more views during the 15-month trial.

Now I'm delighted to report that such content sharing is extended to the entire Springer Nature portfolio, covering more than 2,700 journals and 300,000 new articles a year. That means there's a whole new world of science freely available, just for you. *—M.D.*

Illustration by James Gurney (cover sketch), Illustration by Nick Higgins (DiChristina)

February 2016

BRAIN PLASTICITY

I was disappointed and more than a little angry to find prevention or treatment of autism listed among the uses of new discoveries in neuroplasticity in the otherwise excellent "The Power of the Infant Brain," by Takao K. Hensch. Ironically, in his last paragraph, Hensch brings up a parallel to one of the main objections to such "cure" rhetoric: it represents a neurological change so pervasive as to violate the identity of the treated person. Unlike schizophrenia or amblyopia, autism is not separable from the selfhood of those who have it. Furthermore, such rhetoric promotes incredibly harmful Pavlovian "corrective therapies," such as certain forms of applied behavior analysis.

I am autistic, I've met with and listened to speeches and read essays by dozens of other autistic people, and I can assure you that we do not in fact want to be "cured."

Paul Eisen
via e-mail

Hensch expresses concern that "the rewiring of the brain could threaten to undermine one's sense of self." I do not understand why he views undermining one's sense of self negatively. "Self" is an overvalued, arbitrary human construct. Much has been written about its undesirability in Buddhist philosophy. That outlook goes quite well with his own statement about meditation increasing plasticity and thereby undermining the fixed sense of self.

Prevesh Rustagi
Fort Wayne, Ind.

"'Self' is an overvalued, arbitrary human construct."

PREVESH RUSTAGI *FORT WAYNE, IND.*

BENIGN MICROBES

In "Bitter Taste Bodyguards," Robert J. Lee and Noam A. Cohen refer to "modern society's excessive use of antibiotics" and its many negative consequences. Yet the article is full of references to "invaders" of the body and the need to kill these sources of harm.

Surely, our communal failure to understand and value the symbiotic relationship we have with the overwhelming number of microbes in our environment leads us to do things like buy antibacterial wipes for every household surface and wage continuous war against what in many cases is helpful to us.

It might be a good policy to add some language in any article on disease and infection to the effect that, amid the many beneficial interactions we have with the microbes we are embedded with, the article deals with a harmful interaction.

Ed and Denise McCaffrey
via e-mail

SHOEMAKER-LEVY 9

I enjoyed David H. Levy's retrospective on his lifelong quest for comets ["My Life as a Comet Hunter"]. In late March of 1993, before Levy became an astronomy celebrity, he was scheduled to give a presentation at the Phoenix Astronomical Society in Arizona, where he was a regular speaker.

Levy arrived a few minutes late, waving an envelope and saying, "I hope you don't mind if I change the topic of my talk, but I have something here I think you'll want to see."

I was in charge of A/V at the time, which was still pretty much slides, film or overhead transparencies. While Levy was setting up in the front of the room, he removed a print from the envelope and asked if it could be projected. I explained that we had an opaque projector we could use, but the print would need to be covered by a glass plate to hold it flat under the 200-watt bulb. He expressed some concerns about damage but relented.

The photograph survived fine. It clearly showed the "string of pearls" Comet Shoemaker-Levy 9 on its way in to Jupiter. Levy gave his revised talk, noting that the NASA Jet Propulsion Laboratory had suggested a distinct possibility of impact. The rest is history.

Dan Heim
President, Desert Foothills Astronomy Club

PRENATAL SCREENING

"Beware Prenatal Gene Screens," by the Editors [Science Agenda], highlights the growing role of noninvasive prenatal tests in helping women, with the aid of their physicians, assess their fetus's risk for genetic disease in pregnancy and cautions that such assessments have a higher chance of false positive results than more specialized diagnostic exams do.

Like all clinical tests, noninvasive prenatal tests have limitations. That is why Quest Diagnostics is collaborating with the Perinatal Quality Foundation to create a registry to track false positives and false negatives and to educate women and physicians in the appropriate use of these tests.

Quest has purposefully adopted the phrase "noninvasive prenatal screening" to emphasize that this is a screening test whose positive result should receive "diagnostic" confirmation.

Douglas S. Rabin
Medical director, Women's Health, Quest Diagnostics

HIDDEN PLANET

In "The Search for Planet X," Michael D. Lemonick notes that the strange orbital paths of about a dozen objects (including an ice ball named Sedna) are consistent with this system of objects being perturbed in their orbits by an unknown additional planet—a super Earth (a planet roughly up to 10 times the mass of Earth)—in the remote regions of our solar system. If these orbits can be analyzed

to reveal where the source of the perturbation lies, then it may be possible to find this "Planet X."

Some man-made objects may be getting perturbed as well. Pioneer 10, launched decades ago and now well beyond Pluto, has slowed down more than expected. It's an anomaly with no agreed-on explanation. If Planet X is causing this slowing, could Pioneer be added to the other objects to help find Planet X?

David Howell
Alton, N.H.

Dear Planetary Scientists,
How cruel you were to cast me out
And leave me moaning in disgrace.
I beg you: don't compound the pain—
Don't put another in my place.
Yours truly,
Pluto

c/o Felicia Nimue Ackerman
Professor of philosophy, Brown University

LEMONICK REPLIES: In response to Howell's question: Both the Pioneer 10 and 11 missions slowed excessively on their way out of the solar system. The widely accepted solution to that anomaly is that it was caused by heat emissions from their onboard power supply and instruments. In principle, gravity from an unknown planet could have at least been an influence. In practice, however, the best estimate for the mass and location of the proposed Planet X would make its gravity too weak to account for the slowdown.

ERRATA

"The Search for Planet X," by Michael D. Lemonick, referred to the icy body Sedna as 2,250 kilometers across. That was an early estimate. The figure has since been revised to about 1,000 kilometers. Further, the article gave the distance of the Nemesis star proposed by physicist Richard Muller in the 1980s as "10,000 AU, or about 1.5 light-years." The former figure should have been 100,000 AU.

In the "Periodic Table of Substitute Availability" illustration in "Elemental Urgency," by Jennifer Hackett [Advances], the element thallium was incorrectly given the symbol "Ti." It should have read "Tl."

LETTERS TO THE EDITOR

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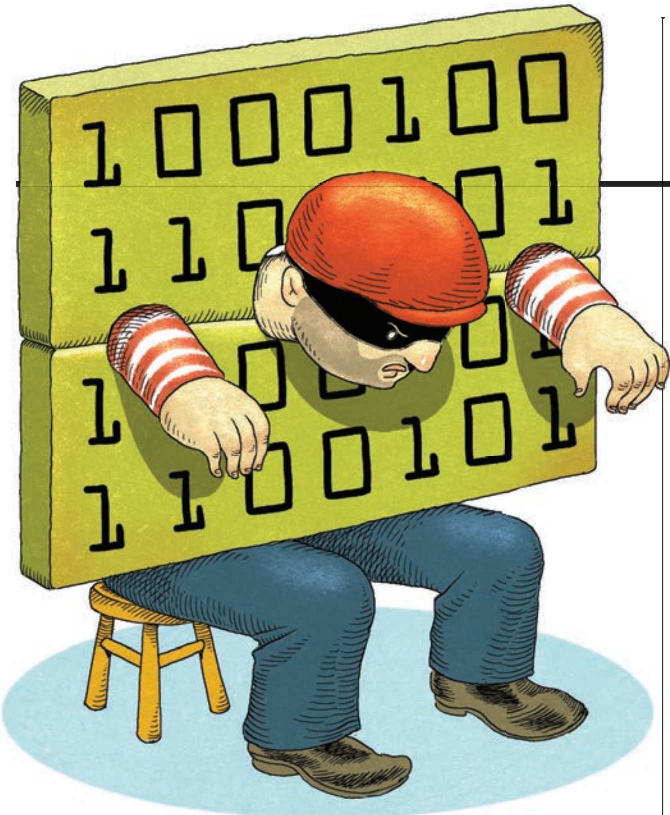

Rules for Cyberwar

Nations must agree on penalties with sharp teeth to discourage state-sponsored cyberattacks

By the Editors

The world is at war. Some might quibble with the characterization of malicious hacking as warfare, preferring phrases such as "cyberespionage" or "cyberconflict." But when governments, industry and individuals are under constant attack by antagonists from all corners of the globe—marauders who use the Internet to steal vital information, sabotage critical operations and recruit terrorists—this means war. It is high time for an internationally coordinated response.

The first skirmish arguably took place in 2007, when online attacks against the Baltic state of Estonia took down critical government, banking and media Web sites. Suspicion soon fell on state-sponsored Russian hackers retaliating against Estonia's removal of a Soviet-era war memorial from the center of the country's capital, Tallinn. The use of proxy servers and spoofed Internet addresses to route the attacks, however, made it very difficult to trace their source, and the Russian government has denied any involvement.

Subsequent international incidents have followed a similar attack-and-deny pattern. The Kremlin has never admitted to launching or sanctioning cyberattacks against Georgian media, communications and transportation companies in advance of Russia's 2008 ground war against that country. Nor has the U.S. officially taken responsibility for the Stuxnet or Duqu malware attacks on Iran from 2007 to 2011, which damaged centrifuges crucial to the country's nuclear program—despite reports that U.S. and Israeli programmers developed those cyberweapons.

Cyberattacks have only escalated since then. The obscure, hard-to-trace origins of these assaults not only protect the guilty party (or parties) from law-enforcement agencies or retaliation, they also create paranoia that puts a strain on international diplomatic relations.

It is difficult to penalize or hit back at an enemy when you aren't sure who it is. In 2015 China emerged as the most likely culprit after the U.S. Office of Personnel Management discovered the theft of more than 21.5 million data records from its computer systems. China's denials, however, set up a familiar stalemate—until the Obama administration last year threatened to levy economic sanctions against Chinese firms that benefited from the hacking of any U.S. entities.

This change of tactics—targeting the results of a cyberattack rather than the source—helped to bring U.S. and Chinese presidents Barack Obama and Xi Jinping to the bargaining table in late September. The two leaders promised, among other things, that neither the U.S. nor the Chinese government would target each other for economic espionage via the Internet and that their countries would cooperate during cybercrime investigations. U.S. and Chinese officials continue to work out the details. A key aspect, of course, is figuring out how this pact will be enforced.

Other countries and international entities are pushing similar agendas aimed at creating a cybertruce. The U.S., China, Russia and several other world powers pledged not to engage in cyberespionage for economic benefit following the Group of 20 conference last November. Members of the U.S. House Intelligence Committee have called on the country's intelligence community to help create international rules of online engagement, which they refer to as an "E-Neva Convention." The United Nations and NATO have likewise weighed in with rules that would prohibit states from intentionally damaging one another's critical infrastructure and from interfering with national emergency response teams defending against cyberattacks.

It will take more than pledges and frameworks, however. These proposals must be legally binding treaties that include fines, penalties and other enforceable mechanisms. They need to actively discourage online aggression and hold nations responsible for misuse of the Internet infrastructure they provide or support. This last part is particularly important because so many cyberattacks against government computers come from shadowy groups acting independently of any nation or state.

A certain degree of cyberconflict is inevitable, but the establishment of international rules of online conduct and penalties for noncompliance is vital to suppress the worst of it. SA

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Illustration by Wesley Bedrosian



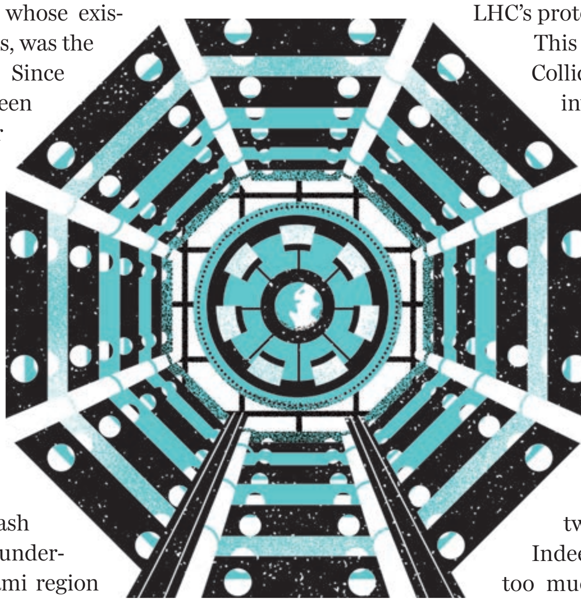
Howard Baer is Homer L. Dodge Professor of High Energy Physics at the University of Oklahoma. **Vernon D. Barger** is a Vilas Professor and a Van Vleck Professor in the physics department at the University of Wisconsin–Madison. **Jenny List** is an experimentalist and staff member at DESY in Hamburg, Germany.

The Collider That Could Save Physics

A proposed Japanese accelerator could solve those mysteries the LHC did not

By Howard Baer, Vernon D. Barger and Jenny List

The 2012 discovery of the Higgs boson at CERN's Large Hadron Collider (LHC) near Geneva was a spectacular vindication of the Standard Model—a framework that describes all known particles and forces in physics. The Higgs, whose existence was first predicted in the 1960s, was the final missing piece of the puzzle. Since then, however, physicists have been stuck. The so-called superpartner particles scientists hoped to find at the LHC—particles whose detection would help solve longstanding problems with the Standard Model—never appeared.



Physicists have been talking for decades about a collider that could find those missing particles. Three years ago an international team of physicists and engineers finished its design. Called the International Linear Collider (ILC), this 31-kilometer-long accelerator would smash electrons and positrons together underneath the mountains of the Kitakami region in northern Japan, producing matter-antimatter annihilations that would release 250 billion electron volts of energy. (A later upgrade would double the ILC's energy output.) Any day now Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) is expected to decide whether the ILC should go forward. We believe it should.

The Standard Model has a hole where a 125-billion-electron-volt Higgs boson would fit perfectly. And that is what scientists found at the LHC. The twist is that physicists cannot explain *why* the Higgs has that mass. (Physicists generally measure the mass of particles in electron volts, which works because energy and mass are equivalent.) In fact, they have known since the early 1980s that virtual quantum effects should make the Higgs millions or billions of times more massive.

The theory of supersymmetry, or SUSY, offers a solution. It posits an underlying link between matter particles, such as quarks and leptons, and force-carrying particles, such as photons, gluons, and *W* and *Z* particles. It also predicts a host of new partner particles with such whimsical names as squarks (partners of quarks) and Higgsinos (partners of the Higgs boson). These partner particles interact with Standard Model particles in a way that cancels out the virtual quantum effects, producing the masses predicted by the Standard Model and observed at the LHC.

Physicists thought they might find these superpartners when the LHC's predecessor, CERN's Large Electron-Positron collider, came online a quarter of a century ago. They did not. When superpartners also failed to appear in the much bigger and more powerful LHC, some physicists panicked.

But there is hope. Recent theoretical research suggests that Higgsinos might actually be showing up at the LHC—scientists just cannot find them in the mess of particles generated by the LHC's proton-antiproton collisions.

This is where the International Linear Collider would shine. The ILC's collisions involve significantly lower energies than the LHC, but the ILC's great advantage is that, unlike its European cousin, it would collide electrons and positrons. Unlike protons and antiprotons, which are made up of quarks and antiquarks, electrons and positrons are truly elementary. Their collisions are much tidier, making any Higgsinos that emerge much more straightforward to detect.

The ILC would take no less than $10 billion to build—about twice the cost of building the LHC. Indeed, the cost of the ILC is probably too much for any single country to bear, so that international participation is vital. But it would be worth it.

Theory predicts that the ILC should create abundant Higgsinos, sleptons (partners of leptons) and other superpartners. If it does, the ILC would confirm supersymmetry, vindicating a model of the subatomic universe physicists have long suspected must be true. Because the Higgsino could make up at least some of the still undetected dark matter that pervades the cosmos, it could also help solve one of the outstanding mysteries of astrophysics. If the superpartners still do not show, science advances nonetheless, as high-energy theorists focus their energies on other theories. Either way, the insights gained would deepen our understanding of the laws of nature—and their implications for the origin and evolution of the universe itself. SA

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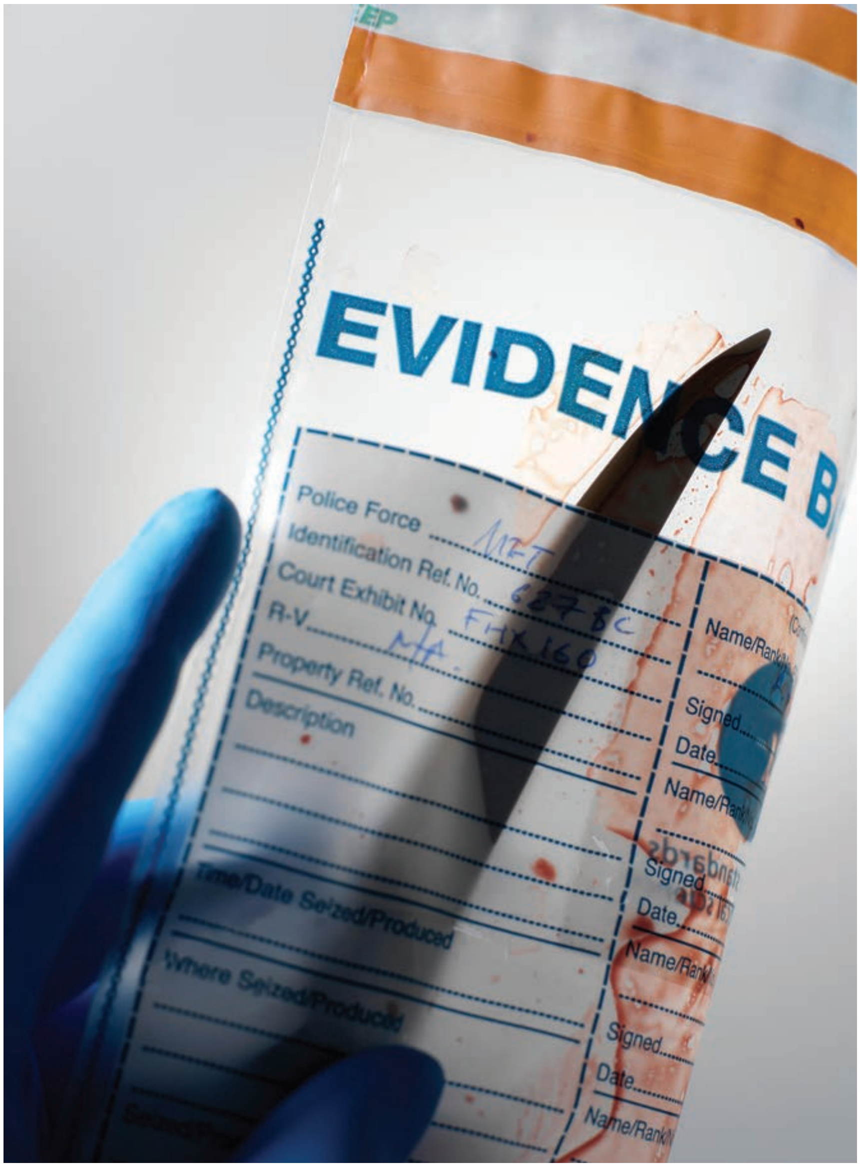
Illustration by James Olstein

ADVANCES

DISPATCHES FROM THE FRONTIERS OF SCIENCE, TECHNOLOGY AND MEDICINE



FORENSIC SCIENCE

When DNA Implicates the Innocent

As with other forensic evidence, confidence in DNA is eroding

In December 2012 a homeless man named Lukis Anderson was charged with the murder of Raveesh Kumra, a Silicon Valley multimillionaire, based on DNA evidence. The charge carried a possible death sentence. But Anderson was not guilty. He had a rock-solid alibi: drunk and nearly comatose, Anderson had been hospitalized—and under constant medical supervision—the night of the murder in November. Later his legal team learned his DNA made its way to the crime scene by way of the paramedics who had arrived at Kumra's residence. They had treated Anderson earlier on the same day—inadvertently "planting" the evidence at the crime scene more than three hours later. The case, presented in February at the annual American Academy of Forensic Sciences meeting in Las Vegas, provides one of the few definitive examples of a DNA transfer implicating an innocent person and illustrates a growing opinion that the criminal justice system's reliance on DNA evidence, often treated as infallible, actually carries significant risks.

As virtually every field in forensics has come under increased scientific scrutiny in recent years, especially those relying on comparisons such as bite-mark and microscopic hair analysis, the power of DNA evidence has grown—and for good reason. DNA analysis is more definitive and less subjective than other forensic techniques because it is predicated on statistical models. By examining specific regions, or loci, on the human genome, analysts can determine the likelihood that a given piece of evidence does or does not match a known genetic profile, from a victim, suspect or alleged perpetrator; moreover, analysts can predict how powerful or probative the match is by checking a pattern's frequency against population databases. Since the mid-1990s the Innocence Project, a nonprofit legal organization based in New York City, has analyzed or reanalyzed available DNA to examine convictions, winning nearly 200 exonerations and spurring calls for reform of the criminal justice system.

Like any piece of evidence, however, DNA is just one part of a larger picture. "We're desperately hoping that DNA will come in to save the day, but it's still fitting into a flawed system," says Erin E. Murphy, a professor of law at New York University

RAFE SWAN *Alamy*

and author of the 2015 book *Inside the Cell: The Dark Side of Forensic DNA.* "If you don't bring in the appropriate amount of skepticism and restraint in using the method, there are going to be miscarriages of justice." For example, biological samples can degrade or be contaminated; judges and juries can misinterpret statistical probabilities. And as the Anderson case brought to light, skin cells can move.

Since 1997, when researchers first showed that it was possible to gather genetic information about a person based on skin cells they had left on an object, this type of trace evidence, also known as touch DNA, has been increasingly collected from surfaces such as door and gun handles. (In some jurisdictions, such as Harris County, Texas, the number of touch DNA cases submitted for laboratory analysis increased more than threefold between 2009 and 2013, often as a means of identifying possible perpetrators for burglaries and thefts.) Commercial companies now sell kits to law-enforcement agencies that can generate a full genetic profile of an individual from as few as three to five cells. Independent labs and scientists working on such projects as identifying long-deceased individuals also employ the kits.

Until recently, this type of DNA has been regarded as incontrovertible proof of direct contact. But a growing number of studies show that DNA does not always stay put. For example, a person who merely carried a cloth that had been wiped across someone else's neck could then transfer that person's DNA onto an object he or she never touched, according to a study published earlier this year in the *International Journal of Legal Medicine.* Similarly, Cynthia M. Cale, a master's candidate in human biology at the University of Indianapolis, recently reported in the *Journal of Forensic Sciences* that a person who uses a steak knife after shaking hands with another person transfers that person's DNA onto the handle. In fact, in a fifth of the samples she collected, the person identified as the main contributor of DNA never touched the knife. Cale and her colleagues are among several groups now working to establish how easily and how quickly cells can be transferred—and how long they persist. "What we get is what we get," Cale says, "but it's how that profile is used and presented that we need to be cautious about."

Biological samples can degrade or be contaminated; judges and juries can misinterpret statistical probabilities. And as the Anderson case brought to light, skin cells can move.

At the forensics meeting in Las Vegas, Kelley Kulick, a public defender for the County of Santa Clara, presented the idea that Anderson's DNA hitched a ride on the medics' uniforms. Just how often transferred DNA ends in a wrongful accusation is unknown. "Although clear cases appear to be quite uncommon, I think it's probably more prevalent than we think," says Jennifer Friedman, a public defender in Los Angeles and DNA specialist. "The problem is that what we don't see frequently is the ability to definitely prove that transfer occurred."

The erroneous interpretation of touch DNA for Anderson has now also become a contentious issue for two codefendants on trial for the Kumra murder, Kulick says. No doubt DNA evidence remains an invaluable investigative tool, but forensic scientists and legal scholars alike emphasize that additional corroborating facts should be required to determine guilt or innocence. Like all forms of evidence, DNA is only one circumstantial clue. As such, Anderson's case serves as a warning that a handful of wayward skin cells should not come to mean too much.

—Peter Andrey Smith

1

2

CONSERVATION

Ugly Critters Get No Love

Scientists would rather study good-looking species, according to a survey of their work

The koala is a cutie, but does it steal too much of the limelight? A new study adds quantitative detail to an ongoing debate over whether such "conservation mascots" receive publicity and funding to the detriment of animals typically deemed less attractive. Researchers at Murdoch University and Curtain University, both in Western Australia, combed through 14,248 journal papers, books and conference proceedings about 331 Down Under mammals and found an overwhelming bias against investigations of "ugly" species. In fact, 73 percent of the publications covered marsupials, such as koalas and kangaroos. In contrast, rodents and bats received 11 percent of the attention, even though they made up 45 percent of the mammals included.

Even worse, most research into these aesthetically challenged animals is at the surface level, including taxonomic descriptions that merely name the species and provide measurements, says lead author Patri-

GETTY IMAGES (1–3)

Spinifex hopping mouse (*1*), broad-toothed rat (*2*) and ghost bats (*3*).

cia Fleming. And without knowledge of their habitats, food sources and behaviors, these creatures are harder to protect against threats that could lead to extinction. Such information gaps afflict animals well beyond Australia, too. “There are many taxa worldwide, such as amphibians, that we know are doing even worse and have even less research into them,” says Simon Watt, founder of the Ugly Animal Preservation Society. These organisms could be more ecologically important than the ones typically held up as worth saving. Bats, for example, help to control pest insects that can carry diseases or devastate crops.

Fleming describes her paper as a call to action for research on more diverse wildlife but acknowledges that funding to study or save unappealing creatures might always be lacking. “It’s a small pie to divide up, and that leaves some species unfunded,” she says. In Australia, for example, most of the federal conservation budget goes toward fighting another group: “bad” invasive species. And whereas elimination of introduced European rabbits might be good for Australia’s native plants, it does little to help the spinifex hopping mouse or ghost bat—let alone the koala.

—John R. Platt

SOURCE: QUINTILLION NETWORKS

TECHNOLOGY

A Northwest Passage for the Internet

The rapid disappearance of Arctic ice may enable an undersea Internet cable to cut the shortest path between Europe and Asia

More than a century ago polar explorer Roald Amundsen and his six-man crew became the first to navigate the icy Northwest Passage. This month much larger ships than Amundsen's will retrace parts of the sea route but not as adventurers. Instead they will begin laying an undersea fiber-optic cable meant to connect Asia and Europe by crossing the Arctic Circle—the shortest practical distance yet for Internet signals traveling between the two continents.

Most of the undersea cables that currently form the backbone of the World Wide Web connect the U.S. to Europe and Asia by crossing the Atlantic or Pacific oceans. But climate change and an accelerating loss of Arctic sea ice during summer months have opened the possibility of northern cable routes. "It is more viable for [companies] to propose these new and innovative routes than ever before," says Nicole Starosielski, a media, culture and communications researcher at New York University and author of the 2015 book *The Undersea Network.*

In this case, Anchorage-based Quintillion Networks hopes its cable can offer high-speed Internet connections to remote communities in Alaska and Canada for the first time. The cable, which is expected to reduce the lag in transmissions between London and Tokyo, may also offer advantages to stock market traders who want the shortest possible delays on millisecond transactions.

Many countries would favor less U.S.-centric cable routes and additional backup lines to avoid U.S. surveillance and disruptions in service, Starosielski says. Such political and economic considerations have whetted the world's appetite to fund the installation of new and potentially more costly cable projects. But only time will tell if the Arctic route and other undersea Internet cable ambitions will pay off in the long run. *—Jeremy Hsu*

Map by Pitch Interactive

PHASE 3
The last phase of the project will extend the undersea cable east from Prudhoe Bay, Alaska, to the U.K. This final leg will traverse the Northwest Passage as it cuts through the waterways of Canada's Nunavut territory and then crosses the Atlantic Ocean. Once all three phases are complete, the entire cable route will enable Internet data to flow between Europe and Asia at speeds as fast as 30 terabits per second.

In March, Arctic sea ice reached its maximum extent for the year at **5.607 million square miles**—the lowest ever recorded since satellites began tracking Arctic sea ice coverage in late 1978.

THREATS TO EXTANT UNDERSEA CABLE

FISH TRAWLING
40% chance of causing a cable break*

SHIP ANCHORAGES
28%

SUBSEA EARTHQUAKES OR SUBSIDENCE
8%

SHUNT (ELECTRICAL) FAULTS
8%

AMPLIFIER OR BRANCHING UNIT FAILURES
4%

ABRASION
(wave, seabed, ice)
3%

OTHER FACTORS
(e.g., sabotage)
9%

*Risk-assessment figures reflect typical threats to cables in the Atlantic and Pacific oceans. For much of the year, ice covering large parts of the Arctic Ocean and surrounding seas may protect this project from the threat posed by fishing vessels.

BY THE NUMBERS

Fast Faults

To feel the earth move under your feet, visit New Zealand. Every year the sides of the island nation's Alpine Fault shift past one another about 30 millimeters—a blistering speed for strike-slip faults, which typically slip at rates closer to one or two millimeters a year. "What is particularly interesting about the Alpine Fault is that it has maintained this high slip rate for almost its entire history," says Simon Lamb, a geologist at the Victoria University of Wellington. "As far as I can tell, no other one land fault comes close in this respect." In fact, the Alpine Fault has shifted approximately 700 kilometers over the past 25 million years—250 kilometers more than previously estimated, according to Lamb's new study in *Geochemistry, Geophysics, Geosystems.* That movement has seismic consequences: New Zealand has a 30 percent chance for an earthquake of magnitude eight or higher in the next 50 years. *—Jennifer Hackett*

Top 5 Fastest-Moving Strike-Slip Faults

FAULT NAME	LOCATION	LENGTH *(km)*	SLIP RATE *(mm/yr)*
Alpine	South Island, New Zealand	700	30
San Andreas	California	1,100	25
North Anatolian	Turkey	1,100	20
Denali	British Columbia to Central Alaska	2,000	10
Altyn Tagh	Tibet	1,500	9

Snow line along the Southern Alps showcases New Zealand's Alpine Fault.

COURTESY OF JACQUES DESCLOITRES AND MODIS RAPID RESPONSE TEAM/NASA/GSFC

Q&A

Lab Tech Opening: 249 Miles above Earth

The first research scientist to visit the International Space Station in four years is set to kick off DNA sequencing in space

Virologist Kate Rubins

COURTESY OF JAMES BLAIR NASA

When Kate Rubins heard back from NASA in 2009, she traded her clean suit for a spacesuit. Rubins, a trained virologist, is a member of the 20th group of astronauts chosen by the space agency, and she is poised to make her first trip to the ISS this month. Since her selection, she has closed up her laboratory at the Whitehead Institute for Biomedical Research in Cambridge, Mass., and undergone extensive training for space that included prolonged underwater sessions and military pilot courses. Onboard, Rubins will be responsible for conducting and monitoring more than 250 experiments from researchers around the world, including an investigation into the mechanics of sequencing DNA in microgravity—a feat first pulled off last fall by Johns Hopkins University researchers onboard a parabola-flying plane. Rubins recently spoke with Scientific American about her upcoming sojourn to space, which will last about four months.

—Jennifer Hackett

Is it rare for an astronaut to be a molecular biologist?

NASA has had biochemists in the past. Scientist-astronauts really started in the Apollo days, when they started bringing geologists in. Lately there's more of a research focus on biology and molecular biology. So far I've worked to upgrade our hood, in which we do biology experiments on the space station. Now we have the capability to maintain a sterile environment for any experiments with living organisms.

Will you be conducting any of your own research up there?

My research on the ground was focused on smallpox, Ebola and viral genomics. For obvious reasons, we're not bringing Ebola to the space station. But the work I've done with dangerous pathogens helps you concentrate and keep your head together in a difficult and high-pressure situation.

What's one of your favorite experiments onboard?

One thing we're trying to understand is how DNA-sequencing technology will work in the microgravity environment. This is really cool for me because very small, portable sequencing devices are also used in the field—during a monkeypox outbreak, for example. The kind of technology they use in a remote field medical center is the same kind of technology you'd probably start designing for an instrument on Mars or deep-space exploration. The really critical question for NASA is whether these devices can detect signatures of life in the universe.

So will you perform the first genetic sequencing in space?

I hope so, if it all works out with the timing. The first part of the experiment is more technology development: looking to see how this kind of sequencing technology behaves in microgravity. We don't know if bubbles will form or how the sequencing reaction will work without gravity. The second part is, What happens to DNA in space? Sequencing DNA on the ISS will enable NASA to see what happens to genetic material in space in real time, rather than looking at a snapshot of DNA before launch and another snapshot of DNA after launch and filling in the blanks. We can also look at epigenetic modifications to the genome caused by radiation, sleep changes, and so on.

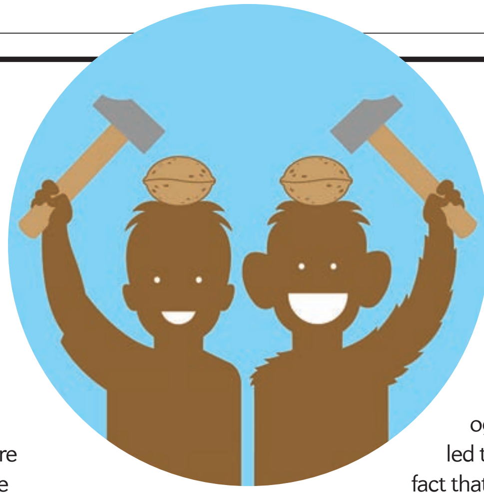
What have you learned that you never expected to?

How to remove and replace jet engines.

COGNITION

Toddlers' Tool Kits

Young children and chimps share some innate abilities



Deep in the lush Mahale Mountains of Tanzania, a chimpanzee strips a twig of its leaves and then plunges it into the ground. When she yanks it out, the twig is crawling with tasty termites. The chimp slurps the insects off the stick before fishing for more six-legged snacks.

Halfway around the world, a three-year-old British child sits before a cardboard box. A small hole reveals three sponges inside. If he can get the sponges out, he will earn a sticker. Without being instructed, the child decides to pick up a nearby Velcro-covered wood rod. He reasons that the sponges might stick to the Velcro, and he is right. In short order, he wins his prize.

In these examples, the Tanzanian primate is simply going about her day. The British primate, however, is participating in an experiment to investigate whether the use of certain tools is instinctual.

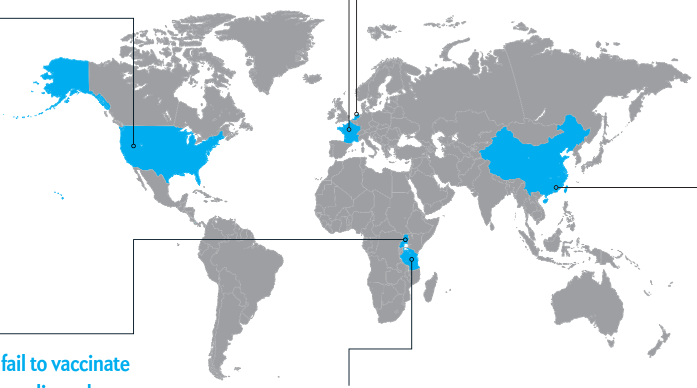
The parallels here are no accident. The research sought to compare the cognitive abilities of humans with those of our great ape relatives by relying on tool-related behaviors recorded in wild chimps and orangutans as a model for tests of young children. In a sample of 50 toddlers between two and three and a half years old, the researchers observed a similar frequency of tool-related behaviors as seen among wild chimps and orangutans. Common ape behaviors, such as fishing for termites, were observed often in the children engaged in analogous scenarios. And behaviors that were more rare in wild ape communities, such as using a rock to break open a nut, were also more infrequently used by the toddlers. In all, the children solved 11 of 12 tests. Psychologist Eva Reindl, who led the study, says the fact that the toddlers displayed the appropriate behaviors is evidence of the children's instinctual ability to use these simple tools.

The results, published in the *Proceedings of the Royal Society B,* undermine the prevailing notion that children need to learn to use tools in all cases—an idea that goes back to Soviet psychologist Lev Vygotsky, who wrote in 1930 that spontaneous tool use by human children was "practically zero." The findings also suggest that humans and other great apes might share a common, innate cognitive apparatus for understanding and manipulating the physical world. *—Jason G. Goldman*

Illustrations by Thomas Fuchs

IN THE NEWS

Quick Hits



U.S.

The Internet Corporation for Assigned Names and Numbers, which distributes IP addresses and Web site domain names, will transition from U.S. stewardship to international oversight. A detailed plan for ICANN operations must be finalized by the end of the summer.

FRANCE

The typical season for harvesting wine grapes is inching ever earlier, according to a new study. Although some consider the change a boon (earlier harvests yield grapes that make higher-quality wine), traditional grape-producing areas may eventually grow too hot for the sensitive crop.

NETHERLANDS

The Ocean Cleanup, an engineering project that plans to take advantage of ocean currents to collect plastic waste, is scheduled to launch this summer off the coast of the Netherlands. The project, led by a 21-year-old, has received millions of dollars in funding and the attention of the public and scientists.

CHINA

The agarwood trees that gave Hong Kong ("fragrant harbor") its name now face extinction because of illegal logging. The trees are highly valued sources of oud oil, an ingredient in fragrances and herbal medicines.

UGANDA

A new law dictates that parents who fail to vaccinate their children against diseases such as polio and meningitis could face up to six months in jail. Similarly, students without verification of their immunizations may be barred from attending school.

TANZANIA

A Belgian organization is training African giant pouched rats to sniff out tuberculosis in prisons in Tanzania and Mozambique. The rats, which have an incredibly sensitive sense of smell, have helped locate land mines since 2003 and could now serve as a speedy and inexpensive way to detect the contagious disease in phlegm samples.

For more details, visit
www.ScientificAmerican.com/jun2016/advances

ANIMAL BEHAVIOR

Eggshell Education

Mother birds may begin teaching their chicks even before they hatch

Red-backed fairy wrens, which inhabit northern and eastern Australia, lay three or four eggs at a time.

In utero, babies can tell the difference between loud sounds and voices. They can even distinguish their mother's voice from that of a female stranger. But when it comes to embryonic learning, birds could rule the roost. As recently reported in *The Auk: Ornithological Advances,* some mother birds may teach their young to sing even before they hatch. Newborn chicks can then mimic their mom's call within a few days of entering the world.

This pedagogy was first observed in 2012 by Sonia Kleindorfer, a biologist at Flinders University in South Australia, and her colleagues. Female Australian superb fairy wrens were found to repeat one vocalization over and over again while incubating their eggs. When broods hatched, the baby birds made the identical chirp to their mothers—a vocalization that served as their regular "feed me!" call.

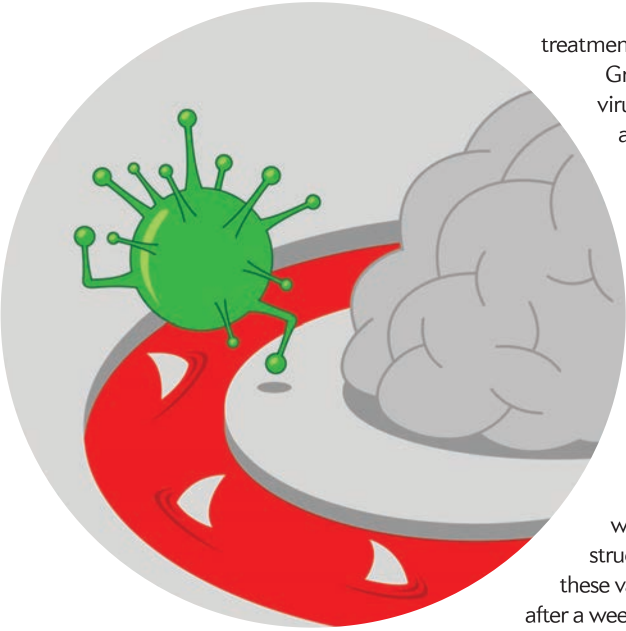
To find out if the trait was more widespread in birds, the researchers sought the red-backed fairy wren, another species of Australian songbird. First they collected sound data from 67 nests in four sites in Queensland from incubation through posthatching. Then they identified begging calls by analyzing the order and number of notes. A computer analysis blindly compared calls produced by mothers and chicks, ranking them by similarity.

It turns out that baby red-backed fairy wrens also emerge chirping like their moms. And the more frequently that mothers had called to their eggs, the more similar were the babies' begging calls. In addition, the team set up a separate experiment that suggested that the nestlings that most closely mimicked their mom's voice were rewarded with the most food.

This observation hints that effective embryonic learning could signal neurological prowess of progeny to parents. An evolutionary inference can then be drawn. "As a parent, do you invest in quality offspring, or do you invest in offspring that are in need?" Kleindorfer asks. "Our results suggest that they might be going for quality."

—Rachel Nuwer

MARTIN WILLIS *Corbis*



BIOLOGY

A Mental Unblock

Could a virus be the way to deliver medicine more widely beyond a wall of cells surrounding the brain?

The brain presents a unique challenge for medical treatment: it is locked away behind an impenetrable layer of tightly packed cells. Although the blood-brain barrier prevents harmful chemicals and bacteria from reaching our control center, it also blocks roughly 95 percent of medicine delivered orally or intravenously. As a result, doctors who treat patients with neurodegenerative diseases, such as Parkinson's, often have to inject drugs directly into the brain, an invasive approach that requires drilling into the skull.

Some scientists have had minor successes getting intravenous drugs past the barrier with the help of ultrasound or in the form of nanoparticles, but those methods can target only small areas. Now neuroscientist Viviana Gradinaru and her colleagues at the California Institute of Technology show that a harmless virus can pass through the barricade and deliver treatment throughout the brain.

Gradinaru's team turned to viruses because the infective agents are small and adept at entering cells and hijacking the DNA within. They also have protein shells that can hold beneficial deliveries, such as drugs or genetic therapies. To find a suitable virus to enter the brain, the researchers engineered a strain of an adeno-associated virus into millions of variants with slightly different shell structures. They then injected these variants into a mouse and, after a week, recovered the strains that made it into the brain. A virus named AAV-PHP.B most reliably crossed the barrier.

Next the team tested to see if AAV-PHP.B could work as a potential vector for gene therapy, a technique that treats diseases by introducing new genes into cells or by replacing or inactivating genes already there. The scientists injected the virus into the bloodstream of a mouse. In this case, the virus was carrying genes that encoded green fluorescent proteins. So if the virus made it to the brain and the new DNA was incorporated in neurons, the success rate could be tracked via a green glow on dissection. Indeed, the researchers observed that the virus infiltrated most brain cells and that the glowing effects lasted as long as one year. The results were recently published in *Nature Biotechnology.*

In the future, this approach could be used to treat a range of neurological diseases. "The ability to deliver genes to the brain without invasive methods will be extremely useful as a research tool. It has tremendous potential in the clinic as well," says Anthony Zador, a neuroscientist who studies brain wiring at Cold Spring Harbor Laboratory. Gradinaru also thinks the method is a good candidate for targeting areas other than the brain, such as the peripheral nervous system. The sheer number of peripheral nerves has made pain treatment for neuropathy difficult, and a virus could infiltrate them all.

—Monique Brouillette

TECHNOLOGY

Eyeglasses, No Prescription Necessary

A new type of lens adjusts its focusing power as needed

As people age, they often require bifocals or several pairs of glasses to see objects both near and far. Deep Optics, a technology start-up based in Israel, is working on an alternative: eyeglasses that automatically refocus on any target at which the wearer looks. The “omnifocals” adjust focal length by relying on the interaction between an electric current and liquid crystal, a material in which molecules act like both liquids and solids.

Although some smartphone camera lenses already include this technology, the effect has yet to be achieved in larger lenses. So far Deep Optics has built a small 20-by-20-millimeter working lens and a distance-detection system—two components that, once integrated, can essentially change the prescription of the glasses in an instant depending on where the person directs his or her gaze. The company plans to have a full-size prototype ready for testing and demonstration in about two years. CEO Yariv Haddad says this technology may also find a place in augmented- and virtual-reality devices, which currently display objects from a single distance and can therefore cause disorienting blurriness. *—Jordana Cepelewicz*

How It Works

1. The wearer trains his or her eyes on an object. Infrared sensors on the frames measure the distance between the pupils and send this information to an embedded processing unit that calculates the distance to the object.

2. Based on the distance calculation, a built-in rechargeable battery sends a particular electric current through the lenses, which comprise three layers. A microns-thick layer of liquid crystal sits between two layers of glass coated with indium tin oxide, a transparent conducting material.

3. As the voltage of the liquid-crystal layer changes, the orientation and distribution of the crystals shift, altering the path that light takes through the lenses. As a result, the refractive index changes. (In conventional eyeglasses, variations in the thickness of the lenses achieve the same effect.) It takes 100 to 300 milliseconds for this adjustment to occur—comparable to the roughly 300 milliseconds it takes the human eye to focus.

RENDERING COURTESY OF ALON SHOAVI

Nancy Shute is a science journalist at NPR. Follow her on Twitter @nancyshute

A Plan to Prevent Gun Suicides

Firearm sellers have become unlikely allies of public health authorities in the effort to keep people from killing themselves

By Nancy Shute

Ralph Demicco feels as though he has watched the 53-minute surveillance video 100 times, searching it for clues to preventing tragedy. He sees a young man walk into his gun shop in Hooksett, N.H. The man asks about buying a handgun. "He engaged the clerk in small talk, totally disarmed the clerk," Demicco says. "No way in heck that clerk would suspect that three quarters of an hour after the conversation that person would take his life."

And yet the 24-year-old man did kill himself, pulling the trigger soon after leaving the boxy beige building. Nor was he the only customer who did so. In one awful week in 2009, he and two other people came into the shop, which Demicco no longer owns, bought guns and used the purchases shortly thereafter to kill themselves.

The experience shook Demicco and prompted him to help found a movement that links members of the firearm community with public health experts to prevent suicides by raising awareness about gun safety, among other things. Its leaders are realists who accept that very strict, European-style gun control is not politically feasible in the U.S. and would, in any case, be a nonstarter for most gun sellers, who oppose such control. But they also know that households that keep guns and ammunition in separate, locked locations and store their guns unloaded have much lower risks of accidental or intentional deaths from firearms. In addition, as a further safety measure, the group seeks to make it socially acceptable for relatives and friends to offer to hold on to a potentially suicidal gun owner's weapons until the crisis has passed.

The public safety campaign is admittedly modest so far, consisting mainly of distributing posters and brochures about suicide to gun shops. Still, its start in a state whose motto is "Live Free or Die" shows that the long-standing political stalemate over gun-control laws need not prevent progress from being made.

EVIDENCE-BASED APPROACH

THE GUN SAFETY COALITION is motivated by data as well as by the distressing stories of gun shop owners. In the case of guns, the impulsive nature of many suicides, combined with the lethal efficiency of firearms, creates an exceptionally deadly pattern.

Several studies now confirm that suicide is often a decision made suddenly. If the moment somehow passes safely, the evidence suggests, lives can be saved in the short and long term.

"There's a fair amount of research showing that the suicide crisis is time-limited," says John Mann, a professor of translational neuroscience at Columbia University who studies suicide. Two thirds of those who survived a suicide attempt, according to one 1991 study, had started planning their course of action less than an hour beforehand. Another study notes that almost half of the 82 people who attempted suicide said they had started thinking about their current attempt less than 10 minutes earlier. Moreover, in the case of guns especially, an investigation by the New Hampshire medical examiner's office showed that nearly one in 10 suicides by firearm from 2007 to 2009 involved a weapon that was purchased or rented the preceding week—often within just a few hours.

National data speak to the other half of this deadly combination. Although guns are not the most popular way that people try to take their life (this dubious distinction belongs to pills), they are the most deadly. Statistics show that 85 percent of attempts with a gun are fatal, compared with 69 percent for hanging and 2 percent for self-poisoning. Mass shootings and murders dominate the news, but 21,334—or nearly two thirds—of the 33,599 gun deaths that occurred in the U.S. in 2014 were suicides. Another 10,945 were homicides.

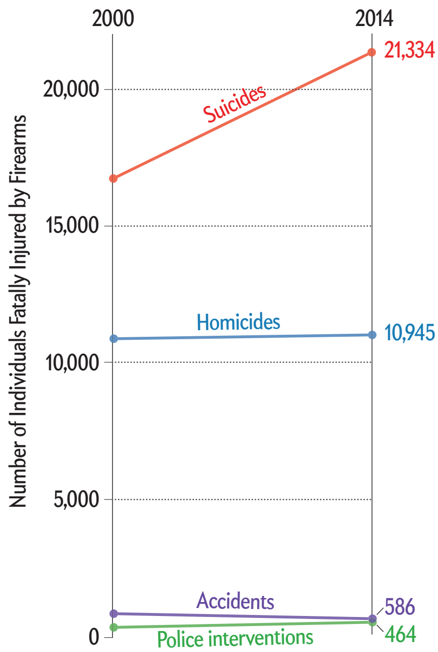
Illustration by Kyle Smart

Guns, then, take what is often an ambivalent decision and turn it into an irrevocable one.

Won't people who are stopped from killing themselves today just find another way to complete the act later? Some number will, unfortunately. Yet most who survive do not keep trying until they succeed. Instead, studies show, the majority of survivors die a natural death many years after failing to kill themselves. The period of greatest vulnerability seems to be in the first year after an attempt, a time when treatment for those who try to end their life is critically important, experts say.

Perhaps the best evidence for the strength of this survival instinct stems from pioneering research carried out by Richard Seiden in the 1970s. Then a clinical psychologist at the University of California, Berkeley, Seiden found that more than 90 percent of the 515 people who were prevented from jumping off the Golden Gate Bridge between the year it opened in 1937 and 1971 eventually lived long enough to die of nonviolent causes. Indeed, Seiden's work spurred such a surge of scientific inquiry by other investigators who reached the same conclusion that state authorities finally agreed to install antisuicide netting underneath the famous span. Bidding to build the barrier is scheduled to finish sometime in 2016.

Suicide Caused the Most Gun-Related Deaths in the U.S. from 2000 to 2014



LIFESAVING RESTRICTIONS

FIGURING OUT WAYS to limit access to particularly lethal methods of committing suicide—whether they are bridges or guns—makes sense from a public health point of view. Yet it also made sense to Demicco and a few other gun shop owners in New Hampshire, who agreed to collaborate with mental health practitioners and researchers after that devastating rash of suicides in 2009. When a public health researcher expressed surprise at the positive response from the firearm community, "a firearm instructor said, 'I could be insulted by that,'" says Elaine Frank, who directs the Counseling on Access to Lethal Means project at Children's Hospital at Dartmouth-Hitchcock and is co-chair of the New Hampshire Firearm Safety Coalition. "'Why do you think the firearm community would be less interested in preventing suicide than you would be?'" In 2011 the group sent posters and brochures to New Hampshire's 65 retail gun shops. The goal was to encourage customers to become alert to signs of crisis in friends or household members and to make firearms inaccessible until the crisis had passed.

"Concerned about a family member or friend?" one poster asks. "Suicides in NH far outnumber homicides." In the photograph, one gray-haired man rests his hand on the shoulder of another. A handgun lies on the kitchen table between them. "Hold on to their guns," the poster continues. "Putting time and distance between a suicidal person and a gun may save a life."

The leaders of the New Hampshire effort did not expect their social-marketing campaign to have a significant effect on the number of suicides right away—and it did not. But 48 percent of the gun shops throughout the state still had the handouts and other materials available for customers after the first year, according to a study published in 2015 in the journal *Suicide and Life-Threatening Behavior*. "That's actually a pretty incredible uptake, especially for a topic like suicide," says Catherine Barber of the Harvard Injury Control Research Center, who is a co-author of the study, along with her colleague Mary Vriniotis, Frank, Demicco and the rest of the New Hampshire Firearm Safety Coalition. "Glancing at one poster isn't going to do the trick," Barber says. "That's like one time seeing a poster about designated drivers. But hopefully it's lighting a match."

Since the New Hampshire project's inception, the model has been adopted or adapted in more than a dozen states, each of which must tailor the concept to its political and legal realities. In Massachusetts, for example, only someone licensed to possess firearms could legally take a weapon for safekeeping, but attaching a trigger lock and giving the key to a trusted friend or relative would accomplish the same purpose.

Utah, which at 21 deaths per 100,000 people has one of the highest rates of suicide in the U.S., is training staff at hospitals and doctors' offices to screen patients for suicide risk and to intervene appropriately. Clark Aposhian, head of the influential Utah Shooting Sports Council, says his group is developing public service announcements aimed at encouraging friends and family of struggling loved ones to get some distance from firearms. "Go over to their house, kind of like a mini intervention at the door," Aposhian suggests. "Put your arm around them and say, 'Let me babysit your guns for a while.'"

It is still too early to know what impact these efforts have had in Utah or elsewhere. But research indicates that Aposhian, Demicco and fellow gun enthusiasts are taking the right steps. Perhaps, as is true of the movement that formed around the slogan "Friends don't let friends drive drunk," championing the safeguarding of guns as a way to reduce suicides will pick up steam in the years ahead. SA

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Graphic by Amanda Montañez

David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Hail, Robo-Taxi

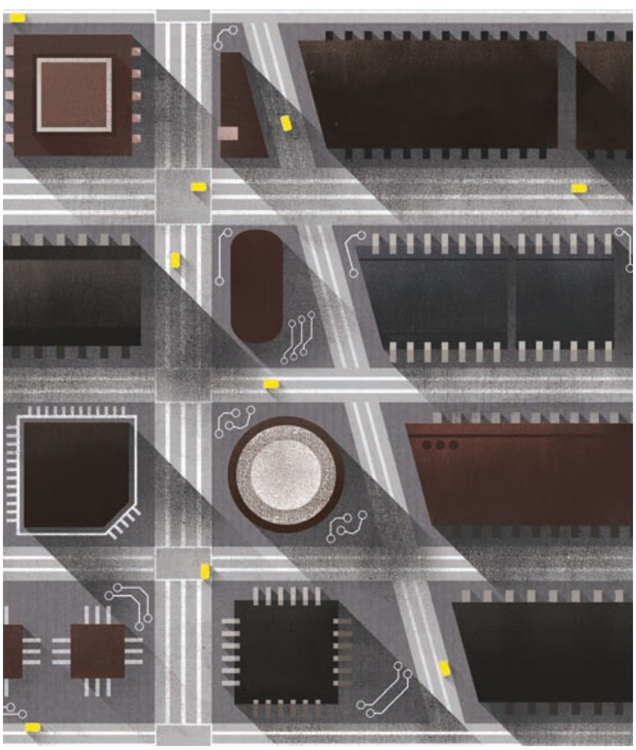
Self-driving cars won't sit idle. They could become a universal, affordable ride service

By David Pogue

No question about it: self-driving cars are big news. Already a long list of car models—from Honda, Volvo, GM, Ford, Audi, Mercedes, Tesla, and others—automate *some* aspects of driving. They offer smart cruise control that goes all the way down to 0 mph, meaning they can drive automatically in stop-and-go traffic, braking and accelerating without ever risking a collision. They can change lanes for you—or stay in the lane for you. They can self-parallel park or head-in park. About the only driving they *can't* yet do themselves is make turns.

The poster child for self-driving cars, of course, is Google's fleet. After driving themselves more than a million miles on public roads, these cars have caused only a single accident so far: a low-speed fender bender with a bus. (They've been in 17 more minor accidents, but all of those were caused by human-driven cars—for example, someone rear-ending the Google car at a stoplight.)

This is exciting stuff. Self-driving cars, in theory, could eliminate the crashes that kill 1.2 million people every year around the world. Trillions of dollars would never have to be spent on hospital stays and insurance payouts. The environment would benefit because driverless cars would take the most efficient route, never get lost and reduce congestion. But the real mind-blower is what will come next: self-driving cars that you *don't* own. Robotic cars that you summon when you want a ride.



Some huge companies are making colossal investments to make this vision real. In February 2015 Uber raided Carnegie Mellon University's highly regarded robotics department, hiring away 40 of its top researchers.

This January, General Motors invested half a billion dollars in Uber's rival, Lyft, for the purpose of developing its own on-demand driverless cars—then topped that two months later by spending a reported $1 billion on Cruise Automation, an automotive tech company. Ford and Google plan a joint venture with similar goals.

Yes, self-driving cars are revolutionary. But *on-demand* driverless cars? The changes would be so massive and fast and global, there's almost nothing about daily transportation that *wouldn't* change—mostly for the better.

Inexpensive robotic rides would mean there would be no particular reason to *own* a car. You wouldn't have to buy one, maintain it, gas it up. You'd never be late because you had to push the snow off the windshield or shovel your driveway.

When you get into a robo-car, you won't have to wait for it to heat up in the winter (or cool down in summer). You'll never have to hunt for a parking space; the car will drop you at the entrance of your destination, then zoom away.

All the societal constructs designed to defend against lousy driving skills—speed limits, speeding tickets, guardrails, even car insurance—might become unnecessary.

Similarly, who will need driver's ed or a driver's license? Twelve-year-olds will get their own rides home from sleepovers. And it won't matter if you (or your parents) are too old, frail or disabled to drive; millions of homebound Americans will suddenly be liberated.

Drunk driving? No longer a problem; if you're not doing the driving, drink up! Feeling sleepy on your long drive? Your robo-Uber car can drive through the night as you nap. And teenagers? Text away!

Of course, there are plenty of details to be worked out [see "The Truth about 'Self-Driving' Cars," by Steven E. Shladover, on page 52]. Some are technical; most of today's driverless cars are still fooled by snow, for example, and don't understand a human officer directing traffic. Some are more remote, though still important: Will robo-taxis be safe from hackers? If they cause an accident, who's responsible—the owner, the carmaker or the software company?

If you prefer to drive yourself, you might still have that option. Some experts predict that self-driving cars in some form will become mainstream on public roads in about five years. It's time to start warming up to the new self-driving era; it's too late to change lanes now. SA

SCIENTIFIC AMERICAN ONLINE
WHAT IT'S LIKE TO DRIVE IN A SEMIAUTONOMOUS CAR:
SCIENTIFICAMERICAN.COM/JUN2016/POGUE

Illustration by Thomas Pullin

EVOLUTION

ASCENT OF THE M

Recent fossil discoveries reveal that evolution began laying the groundwork for their rise to world domination long before the dinosaur-killing asteroid cleared the playing field

By Stephen Brusatte and Zhe-Xi Luo

Illustration by James Gurney

AMMALS

DINO FOR DINNER: A roughly 130-million-year-old fossil of early mammal *Repenomamus* from China was found with the bones of a baby psittacosaur in its rib cage.

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祝大家阅读愉快！

Stephen Brusatte is a paleontologist at the University of Edinburgh in Scotland. His last article for *Scientific American* examined what killed the dinosaurs.

Zhe-Xi Luo is a paleontologist at the University of Chicago. His research focuses on the early evolution of mammals.

ONE EARLY WINTER EVENING IN 1824, ENGLISH NATURALIST AND THEOLOGIAN William Buckland rose to address the Geological Society of London. Anticipation filled the room. Buckland was known for his energetic lectures at the University of Oxford, where he would buzz around in full academic regalia, passing around severed animal parts and fossils to his adoring students. For years there had been rumors that Buckland had gotten his hands on some giant fossil bones, found by workers quarrying roofing stone in the English countryside. After nearly a decade of study he was finally ready to make an announcement. He told the audience that these bones had belonged to an ancient lizardlike animal much larger than any modern lizard. He called it *Megalosaurus*. The crowd was enraptured. Buckland had just unveiled the very first dinosaur.

That evening was a seminal moment in scientific history, touching off humankind's enduring fascination with dinosaurs. But what is largely forgotten is that Buckland made another announcement that day, concerning a discovery much smaller in physical size but equally revolutionary. In reviewing the other fossils found alongside *Megalosaurus* in the stone quarries, Buckland had noted a "most remarkable" find: two tiny mammal jaws, about the size of mouse jaws. Until then, scholars thought mammals were a recent creation, appearing long after primeval geologic eras ruled by giant salamanders and lizards. The two minuscule jaws, their cusped teeth so unmistakably mammalian, were the first sign that this group had a much deeper history.

These jawbones raised a host of questions. How far back in the distant past did mammals originate? What were mammals doing during that long span of history when dinosaurs reigned? How did the classic mammal blueprint—with fur, mammary glands, big brains, complex teeth and keen senses, among other traits—originate? And why did one particular group of mammals—placentals like us (which give birth to live, well-developed young)—rise to dominance, with more than 5,000 species, running the gamut from featherweight bats to behemoth blue whales, spread across the planet today?

For nearly two centuries after Buckland's lecture these questions remained difficult to answer because so few fossils of early mammals were known. A surge of spectacular fossil discoveries over the past 15 years is at last allowing scientists to chart their evolutionary journey from the tiny critters living in the shadow of *Megalosaurus* to the astonishing array of forms that have come to rule the modern world.

MODEST BEGINNINGS

LIKE ALL EVENTUAL DYNASTIES, mammals come from humble stock. In scientific parlance, they are defined as that group on the tree of life that contains the egg-laying monotremes, the marsupials (which raise their tiny babies in a pouch) and the placentals, as well as all the extinct descendants of their common ancestor. The first critters that started looking and behaving like today's mammals were an assortment of stem mammaliaforms, a fancy name for the very closest relatives of true mammals. They themselves evolved from cynodonts—primitive species that still retained many features of their reptilian forebears.

The earliest traces of stem mammaliaforms date to about 210 million years ago, in the Late Triassic period—a heady time in evolution. A few tens of millions of years earlier, nearly all life

IN BRIEF

Scientists have long wondered when and how mammals came to be the dominant vertebrate creatures on the earth. But relevant fossils eluded them.

A stream of finds over the past 15 years has helped document the rise of this group and clarify the role that the dinosaur extinction played in its ascent.

The discoveries reveal that mammals got their start far earlier than experts had once imagined possible and that they evolved a number of specializations while the dinosaurs still ruled.

The eventual demise of the dinosaurs allowed placental mammals in particular to flourish.

was extinguished in a volcano-triggered mass extinction that marked the end of the Permian period and ushered in the Triassic. After most of the giant amphibians and reptiles that ruled the Permian died out, many of today's most important animal groups rose up in the postapocalyptic vacuum. Turtles, lizards, frogs, crocodiles, dinosaurs (which eventually became birds) and the mammaliaform forerunners of mammals all got their start during this time of radical change.

Some of the best fossils of Triassic mammaliaforms come from rocks surrounding an icy arm of the Arctic Ocean called Fleming Fjord that cuts into the coast of eastern Greenland. A wealth of tiny teeth and jaws found there in the 1990s has helped paint a portrait of the immediate ancestors of mammals. These fossils were not easy to come by. Farish Jenkins of Harvard University, a legendary paleontologist who died in 2012, and his intrepid team pried them from the frozen rocks. Jenkins was just as engaging and dramatic in his lectures as Buckland. The debonair professor dressed in beautifully tailored suits and drew meticulous chalk diagrams of skeletons and organ systems in his anatomy lectures. A former U.S. Marine, Jenkins was a daring leader of fossil expeditions who always carried a rifle to protect his Arctic teams from that constant danger of high-latitude fieldwork: polar bears.

Jenkins's crews discovered fossils of three main types of stem mammaliaforms: kuehneotheriids, morganucodonts and haramiyidans. All were small, shrew- to mouse-sized animals that had already developed several important mammal hallmarks. Most notably, they were covered in fur, which provided insulation from the cold and helped to dissipate heat when temperature rose. And their skulls had a simplified hinge joint that worked with enlarged jaw-closing muscles to both strengthen and fine-tune chewing movements, compared with the haphazard bite-and-swallow technique of cynodonts. Cusps on the teeth, particularly the molars at the back of the jaws, made chewing even more efficient.

Fossils from Greenland and other continents reveal that a landmark shift in tooth development accompanied those innovations in the jaw. Whereas cynodonts had teeth that continuously grew, shed and regrew throughout life, the stem mammaliaforms exhibited our familiar pattern of baby teeth being replaced by adult teeth. Although we humans may curse our peculiar dentition when we lose teeth as adults and cannot grow new ones, our unique modes of tooth growth and replacement are intimately related to one of the signature features of mammal biology. Youngsters without teeth or with baby teeth can nurse on their mother's milk, produced by the mammary glands that give the mammal group its name. These stem mammaliaforms would thus have likely nourished their young in the same way as modern mammals, a watershed evolutionary change that allowed mammals to grow faster, allowing for better survival of their young, and to attain higher metabolisms that enabled stem mammaliaforms to be active in colder environments, especially in the darkness of night.

The stem mammaliaforms show the beginnings of other key mammal traits, too, including some that heightened intelligence and sensory perception. Advances in CT scanning over the past decade have allowed paleontologists to visualize details of the internal anatomy of fossilized bone, including brain cavities and nerve paths. This technology has revealed that these early mammals possessed huge brains compared with those of their ancestors, although they were not so enormous as modern mammal brains. They also had larger olfactory bulbs and auditory regions that imparted keen senses of smell and hearing and expanded brain regions that processed tactile input from skin and hair. They even upgraded their inner ear by surrounding it with solid bone to insulate the sensitive hearing apparatus from the loud noises caused by chewing.

Although they were starting to acquire some nifty features of modern mammals, the tiny Triassic stem mammaliaforms were hardly the dominant animals of their day. That distinction belonged to dinosaurs and crocodiles, which were beginning to reach monstrous sizes and ascend to the top of the food chain. But what these protomammals lacked in size, they made up for in variety. Recent research led by Pamela Gill of the University of Bristol in England has revealed a surprising diversity of dietary adaptations among these creatures. Using synchrotron beam lines to scan mammaliaform teeth and engineering software to model their function, Gill and her colleagues showed that morganucodonts had strong enough jaws to crush large insects with crusty exoskeletons, such as beetles, whereas kuehneotheriids had gracile jaws and delicate teeth that could probably handle little more than soft worms or moths. Additional work by one of us (Luo) illustrates that haramiyidans could slice and grind small plants with their uniquely mobile jaws.

THE JURASSIC BIG BANG

The stereotypical view of mammal evolution holds that these protomammals stagnated for tens of millions of years during much of the Mesozoic era (the interval between 252 million and 66 million years ago that comprises the Triassic, Jurassic and Cretaceous periods). While their dinosaur overlords reigned supreme, the protomammals were relegated to an unremarkable existence as small insect eaters that lived on the ground and scurried through the undergrowth. But a flood of new fossil discoveries from locales across the globe has put the lie to this notion. The adaptability seen in the stem mammaliaforms was to become a common motif throughout the evolution of mammals, including the long period over which they overlapped with dinosaurs, and this propensity for adapting to change by diversifying appears to have been a key to their success.

In the case of the stem mammaliaforms, their sharp senses and fine-motor coordination (both enhanced by larger brain size), along with elevated metabolism, enabled them to thrive in the cold and dark of the night. These same characteristics may have helped them survive when another catastrophe struck. The geologic record shows that as the Triassic gave way to the Jurassic, about 200 million years ago, the supercontinent Pangaea tore apart. Volcanoes spewed from the widening cracks between the emerging continents, poisoning the atmosphere and causing ecosystems to collapse. The stem mammaliaforms were apparently able to make it through this hellacious event, establishing themselves in niches not accessible to many other vertebrates of the time.

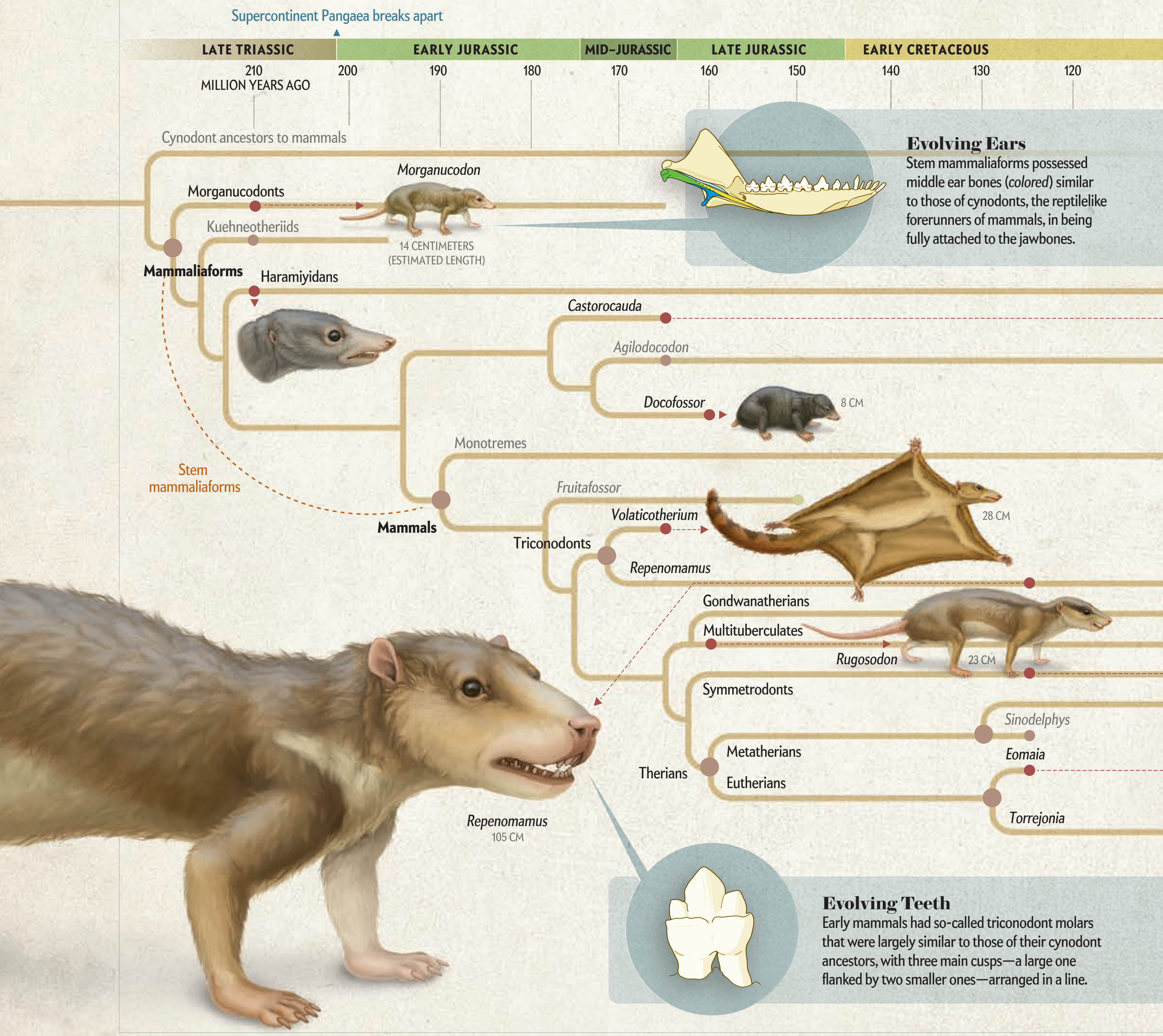
Many dinosaurs managed to survive the end-Triassic mass extinction, and this group still headlined the Jurassic. But 30 million years into that interval, the mammal lineage underwent another, far larger burst of evolution. Much of the evidence for this explosion of new forms comes from the thousands of stunning fossils that have been collected over the past decade from

From Shrew to You

Recent fossil discoveries have allowed researchers to reconstruct the evolution of mammals from their humble, shrewlike ancestors to the extraordinary variety of forms, including humans, that exist today. Changes in the teeth and ears of mammals were among the key innovations that helped to fuel their success, allowing them to invade all manner of ecological niches.

Modest Beginnings
The earliest creatures that resembled mammals, the stem mammaliaforms, got their start when the earth's continents were still joined in a single landmass.

Early Specialization
Researchers once thought mammal evolution stagnated until the dinosaurs died. But new evidence shows mammals evolved a wide range of feeding and locomotion styles while dinosaurs still ruled.



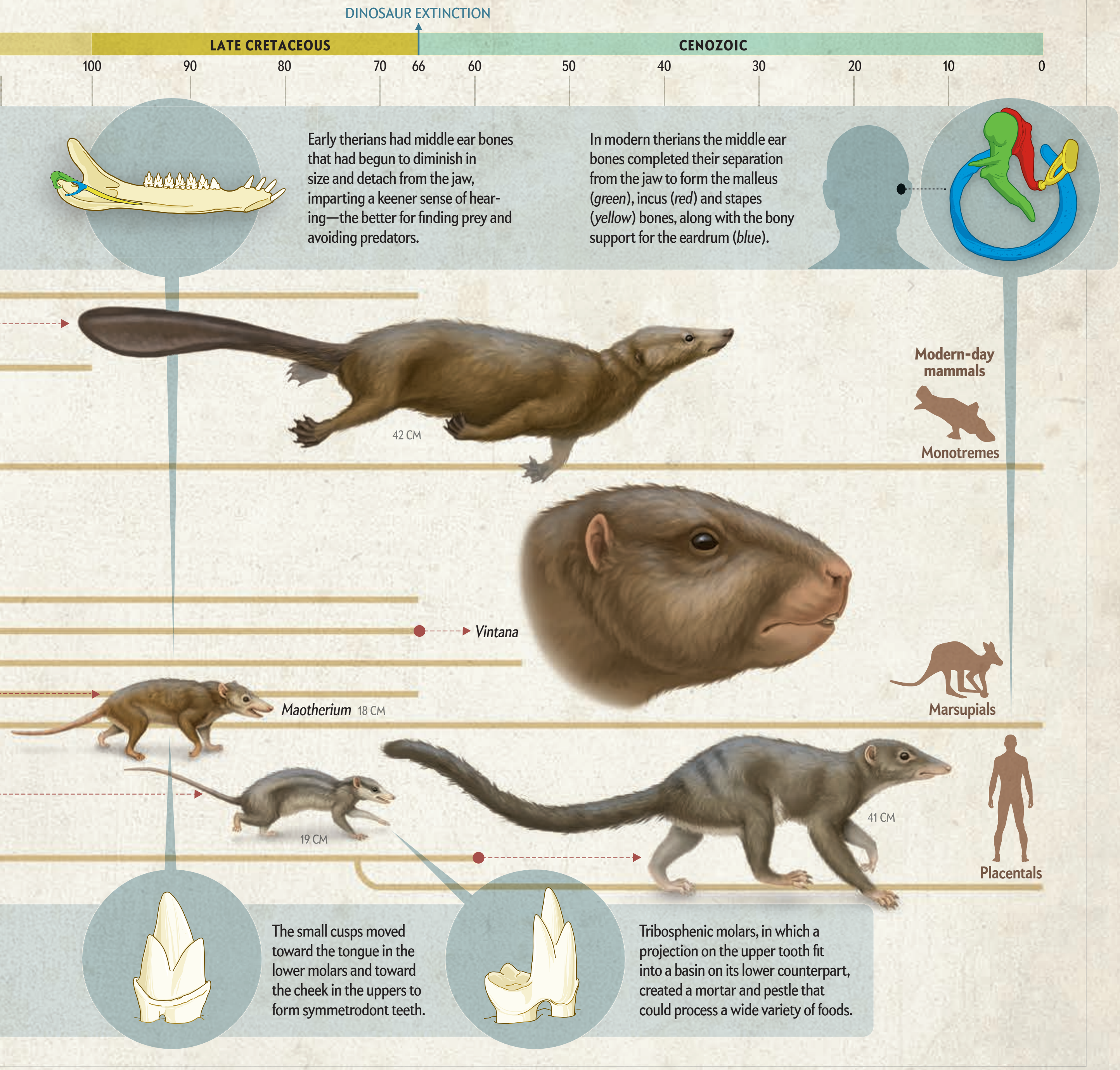
Illustrations by April Neander (reconstructions), Design by 5W Infographics

Mammals Abloom

The emergence of flowering plants spurred the evolution of the therian mammals, the group that includes the pouched marsupials and the placentals, which give birth to well-developed young.

Out with the Old

Although mammals had significant successes during the age of the dinosaurs, extinction of those reptiles allowed placentals in particular to diversify spectacularly to fill the newly vacated ecological niches.



the Tiaojishan rock formation in northeastern China. These exquisitely preserved specimens include fossils of insects, feather-clad dinosaurs and more than two dozen mammal skeletons, many surrounded by a halo of wispy hair. About 160 million years ago these animals had the misfortune of living in lakes and forests that were periodically bombarded by volcanic eruptions, which killed and entombed them before they could decay.

Studies of these Chinese fossil mammals conducted by Luo and other researchers, including a team led by Jin Meng of the American Museum of Natural History in New York City, show that these creatures possessed a remarkable variety of body types that allowed them to invade a wide array of ecological niches. *Castorocauda,* a late-surviving stem mammaliaform, was a prairie dog–sized creature with webbed hands and feet and a flattened tail like a beaver's. It is the earliest known swimming mammal. *Docofossor* burrowed underground with shovel-like clawed hands, and its wide fingers had a fused joint, bringing to mind modern African golden moles. *Agilodocodon* was an agile tree climber that fed on sap by gnawing through tree bark with its spade-shaped teeth. Perhaps the strangest of all was *Volaticotherium,* which would have looked like a flying squirrel when gliding between branches, riding air currents with a membrane stretched between its arms and legs. And these specialized mammals were not restricted to China. *Fruitafossor* from Colorado, described by Luo and John Wible of the Carnegie Museum of Natural History in Pittsburgh, was an ant-eating digger. All told, the new Jurassic mammal fossils exhibit almost every major way of life seen in today's small mammals.

TINY TREE CLIMBER *Agilodocodon scansorius,* a 165-million-year-old fossil mammal from China, shows that adaptations to an arboreal way of life evolved earlier than experts once thought.

During the Middle Jurassic, 174 million to 164 million years ago, the number of mammal species skyrocketed. Statistical analyses by Roger Close, now at the University of Birmingham in England, that map skeletal characteristics onto a genealogy to calculate rates of anatomical changes over time show that these Jurassic species were evolving remarkably faster than the stem mammaliaforms of the Triassic—up to twice as fast at times. This accelerated pace of change laid the foundation of the mammal family tree: through it, the lineages leading to today's monotremes (the egg layers) and therians (the broader group that comprises the marsupials and placentals) diverged from each other, like two siblings setting out to form their own broods.

Although many of the diverse Jurassic mammals described here belonged to now extinct lineages sandwiched between the monotremes and therians on the family tree, they are nonetheless vitally important to understanding the origins of extant mammals because they help to reveal the morphology of those mammals' ancestors. These long-dead genealogical branches flourished alongside the forerunners of today's mammals during the Jurassic and later in the Cretaceous before they disappeared. And they experimented with many of the same feeding and locomotion styles, converging on one another and on modern mammals' ancestors in an evolutionary frenzy. Researchers are thus keen to unravel why these early specialists failed to survived to modern times.

FLOWER POWER

BY THE DAWN OF THE CRETACEOUS PERIOD, about 145 million years ago, the modern mammal blueprint was established. Big brains and fast growth rates continued to be key traits of the group. And a new, seemingly minor evolutionary change had emerged as a game changer: the advent of so-called tribosphenic molars, in which a projection on the upper molar fits into a basin on the corresponding lower molar and the two work together to crush food just like a mortar and pestle. This tooth arrangement opened a whole new realm of dietary possibilities to mammals.

Armed with the functionally more versatile tribosphenic teeth, therians began to diversify. The evolutionary lines that would eventually lead to today's major mammal groups—the eutherians that evolved into placentals and the metatherians that later became marsupials—splintered off from one another and started down separate evolutionary paths. Remains of the oldest and most primitive members of these lineages come from China, where they scurried on the forest floor under the feet of feathered dinosaurs well before 125 million years ago.

Although these pioneering therians were around in the early part of the Cretaceous, it was not yet their time to shine. They were few and small, rarely much larger than a gerbil. Instead slightly more primitive mammals known as triconodonts and symmetrodonts presided over the mammal scene for the first 30 million years of the Cretaceous, continuing their earlier successes of the Jurassic. Some of these species were the largest mammals of the entire Mesozoic—such as the meter-long, 14-kilogram *Repenomamus,* a wolverine-sized creature from the Early Cretaceous of China whose fossilized stomach contents included the bones of small dinosaurs.

Then something unexpected happened, an event that would reset the course of mammal history. A totally new type of plant evolved—angiosperms, the flower- and fruit-bearing shrubs and trees that make up most of today's plant species, provide many of our dietary staples and decorate our gardens. During the middle part of the Cretaceous, angiosperms colonized landscapes across the world, providing mammals with new sources of food: the fruits and flowers themselves and the insects that fed on them. The tribosphenic molars of therians, with their dual crushing and shearing abilities, were perfect tools for processing this new fare, and the therians proliferated as a result. Meanwhile mammals with more primitive dentitions, such as the dinosaur-eating *Repenomamus,* went into decline and never made it out of the Cretaceous.

Even with this new windfall of feeding opportunities, the success of the therians was still not assured, however. Competi-

COURTESY OF ZHE-XI LUO

tion was brewing. While therians were feasting on bugs during the middle and later parts of the Cretaceous, some other, more primitive mammal groups evolved complex dentitions that were well suited to slicing and grinding the new angiosperms. The northern continents became overrun by multituberculates—bucktoothed vermin that looked like rats. Despite appearances, these creatures were not closely related to true rodents but rather converged on a rodentlike body plan because they were eating similar foods. Recent studies by Gregory Wilson of the University of Washington and David M. Grossnickle of the University of Chicago have applied sophisticated statistical analysis to big databases of fossil measurements to show that multituberculates were thriving in the latest part of the Cretaceous. They were evolving into many species, growing to ever larger sizes and developing more intricate molars in a coevolutionary dance with the spreading angiosperms.

The southern continents appear to have hosted competitors to therians, too. Paleontologists still know very little about those southern mammals from the latest Cretaceous, but provocative new finds suggest that a weird group was prospering: the gondwanatherians (which, despite their name, were not true therians). For many decades the only records of these mysterious mammals were isolated teeth: high-crowned molars with enamel that grows throughout life like those of horses and cows—ideal for grinding tough plant material. In 2014 a team led by David Krause of Stony Brook University unveiled the first skull of a gondwanatherian, which belonged to a new species called *Vintana* that lived in Madagascar in the very latest Cretaceous. It resembled a beaver and possibly fed on some of the first evolving Cretaceous grasses.

FROM CATASTROPHE, OPPORTUNITY

DURING THE FINAL STANZA of the Cretaceous, some 66 million years ago, mammals were doing well on the whole. Certainly they had come a long way since their Triassic debut, with many insect-eating therians, plant-munching multituberculates and gondwanatherians woven into the food webs topped by big dinosaurs such as *Tyrannosaurus.* They were still limited to inhabiting the understory, however, unable to push out into new kinds of habitats.

But their fortunes—and indeed those of many other organisms—changed in an instant when an asteroid shot down from the sky, unleashing a cocktail of wildfires, tsunamis, earthquakes and volcanic eruptions that reshaped the earth in a matter of days and weeks. These catastrophes and longer-term climatic and environmental changes triggered by the asteroid were too much for the dinosaurs. And just like that, these majestic creatures that had prevailed for more than 150 million years were swept into the dustbin of prehistory.

Mammals also felt the pang of extinction. Evidence for their decline has come from a prominent fieldwork program originally led by William Clemens of the University of California, Berkeley, and now led by Wilson, which for five decades has meticulously collected fossils from across the extinction interval in Montana. The findings show that many larger mammals and those with more specialist diets went extinct with the dinosaurs. The metatherians that were beginning to flourish in the Late Cretaceous were nearly wiped out, and if not for a few plucky species that survived the gauntlet, their descendants, the modern kangaroos and koalas of Australia, would have never had the chance to evolve.

Among the other mammals that made it through were some of the earliest placentals—those species like us that give birth to relatively well-developed young. Molecular clock studies, which calculate when distant ancestors diverged from one another based on DNA differences in living species, indicate that the common ancestor of placentals evolved alongside the dinosaurs in the Cretaceous. But only after the end-Cretaceous extinction did these advanced mammals burgeon and split into the major modern subgroups, including rodents and primates. The reason for their sudden about-face is clear. With *Tyrannosaurus, Triceratops* and kin out of the way, these placentals now had a clear playing field to conquer, and once again they quickly evolved to fill available niches.

Although researchers have long suspected that the death of the dinosaurs was instrumental in the rise of mammals, we now have a far better understanding of the exact role it played: specifically, it was the spark that ignited a placental revolution. Like all revolutions, this one happened very quickly, on the order of thousands of years, a pittance in geologic terms. One of us (Brusatte) has been doing fieldwork in New Mexico to better understand the many facets of this critical moment in evolution, from which mammals made it through the catastrophe to how the diets and behaviors of these survivors aided them in this postapocalyptic world. There the candy-striped badlands of the Nacimiento Formation hold the world's best record of how mammals blossomed after the dinosaurs died. Brusatte's colleague Thomas Williamson of the New Mexico Museum of Natural History & Science has been scouring these rocks for more than 25 years and has collected many thousands of fossils, almost every one of which he can recall in precise detail, thanks to his photographic memory. The fossils consist of jaws and teeth belonging to a myriad of mammal species ranging from shrew-sized insectivores to saber-toothed meat eaters and herbivores the size of cows. They lived a mere 500,000 years after the asteroid hit, a testament to how rapidly placentals were taking over the planet once they got their chance.

Because of their success, we humans are here to tell the tale. Among the placentals that Williamson has unearthed in New Mexico is a skeleton of a puppy-sized creature, called *Torrejonia,* with gangly limbs and long fingers and toes. It lived about 63 million years ago, but when looking at its graceful skeleton, you can almost picture it leaping through the trees, its skinny toes gripping onto the branches. *Torrejonia* is one of the oldest known primates, a distant cousin of ours. Another 60 million years or so of evolution would eventually turn small protoprimates into bipedal-walking, philosophizing apes. Just another chapter in the mammals' evolutionary journey, now 200 million years long and counting. SA

MORE TO EXPLORE

The Origin and Early Evolution of Metatherian Mammals: The Cretaceous Record. Thomas E. Williamson, Stephen L. Brusatte and Gregory P. Wilson in *ZooKeys,* Article No. 465. Published online December 17, 2014.

An Arboreal Docodont from the Jurassic and Mammaliaform Ecological Diversification. Qing-Jin Meng, Qiang Ji, Yu-Guang Zhang, Di Liu, David M. Grossnickle and Zhe-Xi Luo in *Science,* Vol. 347, pages 764–768; February 13, 2015.

FROM OUR ARCHIVES

What Killed the Dinosaurs. Stephen Brusatte; December 2015.

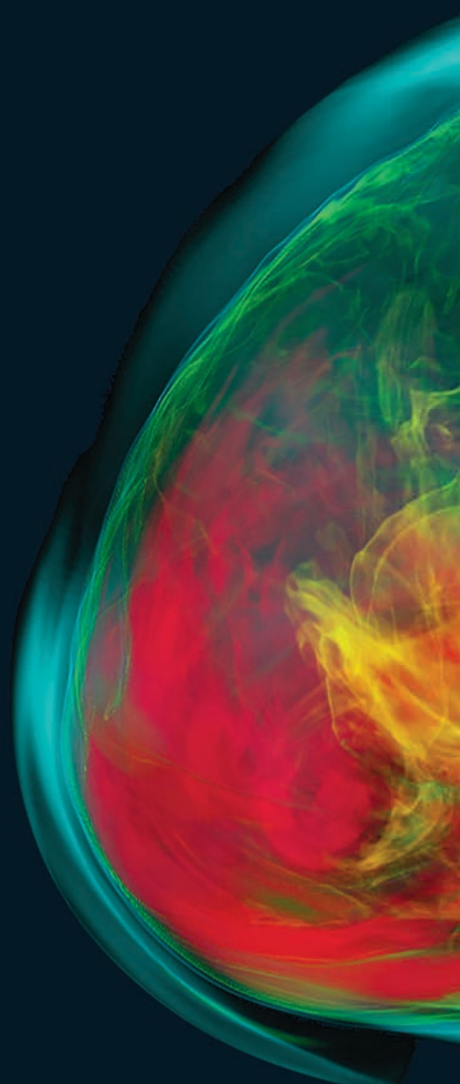
scientificamerican.com/magazine/sa

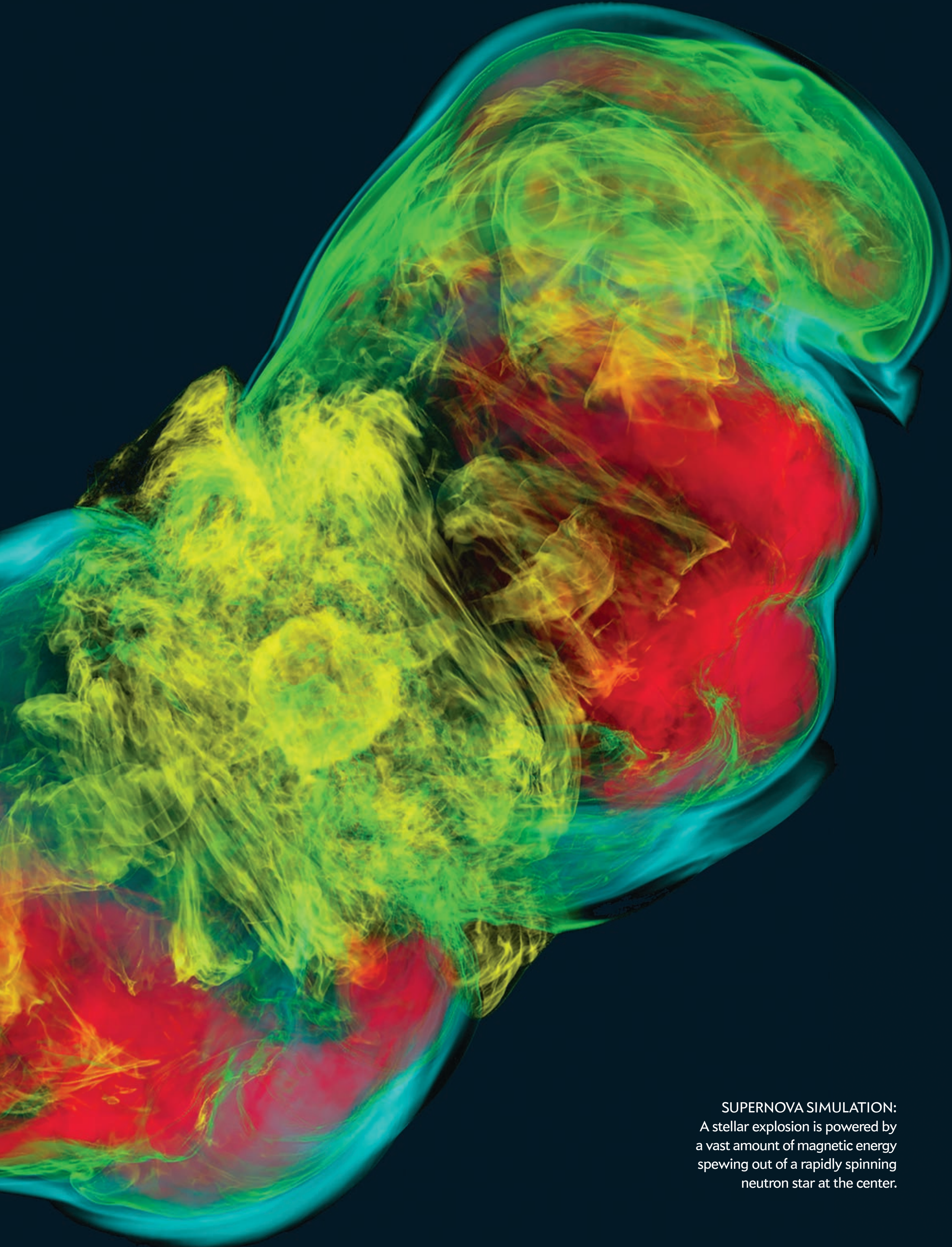
ASTROPHYSICS

STELLAR FIREWORKS

Every year thousands of exploding stars appear in a bizarre assortment of forms. Astronomers want to know what makes them go boom

By Daniel Kasen





SUPERNOVA SIMULATION:
A stellar explosion is powered by a vast amount of magnetic energy spewing out of a rapidly spinning neutron star at the center.

Daniel Kasen is an astrophysicist at the University of California, Berkeley, and at Lawrence Berkeley National Laboratory. His research focuses on developing new theoretical and computer models to explain the many types of stellar explosions in the universe.

ROUGHLY EVERY SECOND, SOMEWHERE IN our observable universe, another sun is destroyed in a stellar catastrophe—when a star pulsates, collides, collapses to a black hole or explodes as a supernova. This dynamic side of the universe, lost in the apparent calm of the night sky, has lately come to the forefront of astronomical research. For almost a century scientists have tried to trace what has happened over billions of years of cosmic evolution, but it is only recently that we have begun to parse celestial events on timescales of days and hours and so witness the volatile lives and deaths of stars.

Although in the past we have lacked tools to study these phenomena in detail, evidence of the universe's transience has been around for millennia, going back at least to Chinese observations in A.D. 1006 of a "guest star" that became visible to the naked eye for a few weeks before fading away. The great astronomer Tycho Brahe recorded a similar event in 1572, as did Johannes Kepler about 30 years later. We now understand these apparitions to be the supernova explosions of stars. At their peak, supernovae can shine brighter than a billion suns, but because most occur very far away, they appear to us as dim specks of light, easily lost in a big sky.

Modern technology is now revolutionizing the study of the dynamic universe. Telescopes have become robotic and outfitted with high-resolution digital cameras that feed data to computerized image processing and pattern-recognition software. The machines monitor large swaths of sky on a regular basis, keeping a digital eye on anything that goes bump in the night. Over the past decade or so this newfound technological capability has enabled astronomers to discover thousands of new stellar explosions every year—each week we find as many new supernovae as had been seen in the entire 20th century.

Not only are we collecting more supernovae—we are uncovering bizarre new species. Some stellar explosions shine exceedingly bright, 100 times more luminous than ordinary supernovae; others are 100 times as dim. Some are colored deep red; others are ultraviolet. Some shine brightly for years; others fade away in a few days. Stellar deaths are turning out to be vastly more diverse than we had realized.

Astronomers are still trying to figure out what drives these odd stellar explosions. Clearly, they are telling us something important about the lives and deaths of stars and about physics under the most extreme conditions of temperature, density and gravity. By studying the full menagerie of supernovae, we hope to finally learn what causes stars to crumble and transform into dead stellar remains such as black holes.

Supernovae also have something to teach us about our own origins. After the big bang the universe contained mostly the lightest of atoms: hydrogen and helium. According to theory, everything else we encounter—the calcium in our bones, the iron in our blood—was fused and expelled in exploding stars. Scientists used to think that run-of-the-mill supernovae created all of the heaviest elements, but the discovery of so many off-kilter explosions now suggests that different squares on the periodic table may have different points of origin. By observing large numbers of diverse supernovae, we are getting closer to pinning down how an assortment of stellar explosions may have contributed to the blend of elements that make up our planet and all its life.

STELLAR CATASTROPHE

TO UNDERSTAND HOW odd some of the supernovae we are discovering are, let us first consider the typical supernova, which is itself a truly remarkable phenomenon. A star is a type of stable nuclear reactor: a massive ball of plasma, bound together by gravity and powered by nuclear fusion in its compressed core. The heat from fusion provides a pressure that counteracts the inward pull of gravity. A supernova explosion represents some kind of catastrophic instability in this balance of forces—the runaway victory of gravity over nuclear burning, or vice versa.

The most common type of supernova occurs in moderately

IN BRIEF

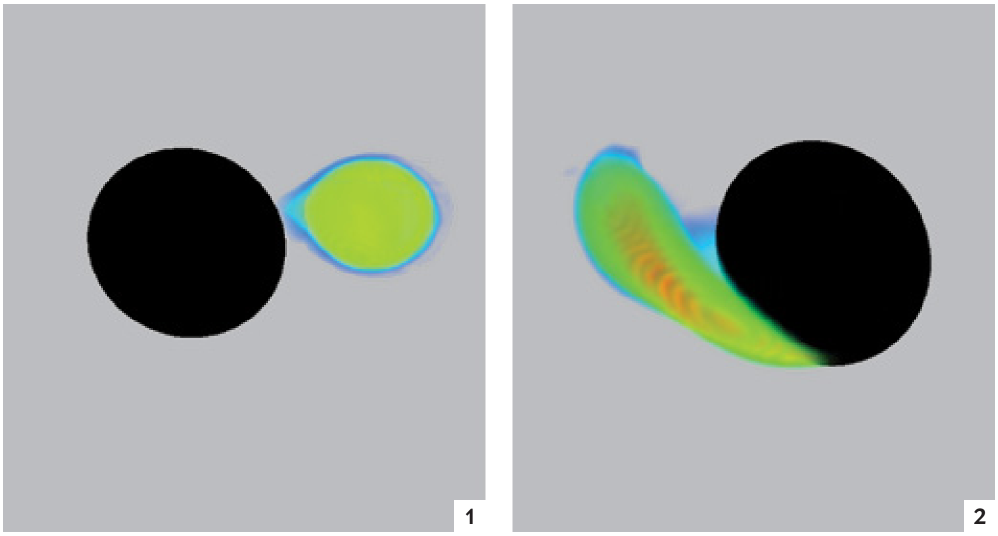
The advent of automated telescopes that quickly scan the sky has revealed a wealth of unusual supernovae, including stellar explosions that are 100 times brighter than normal, as well as unexpectedly dim supernovae that barely make a bang.

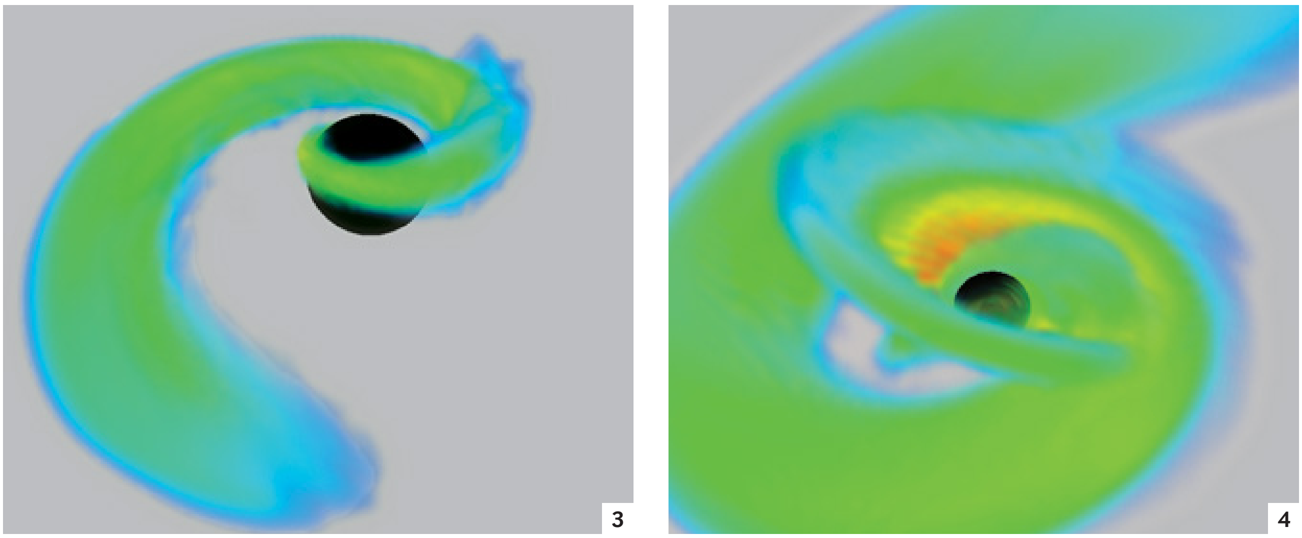
Scientists have several theories about what types of stars might be creating these oddball events and how they might give rise to the heavy chemical elements that populate our planet and our bodies.

Future observations should help answer many fundamental questions about how stars live and die and how they affect life on Earth.

PRECEDING PAGES: COURTESY OF PHILIPP MOESTA *University of California, Berkeley*

COLLISION: A neutron star (*green*) merges with a black hole in this simulation. The process is similar to what scientists think happens when two neutron stars coalesce—a scenario that could explain some underluminous supernovae. Here the neutron star gets distorted by the black hole's gravity (*1* and *2*). A bit of matter is ejected in a tail (*3*), and the rest wraps around the black hole (*4*). Ultimately almost all of the neutron star is swallowed.





COURTESY OF FRANCOIS FOUCART *Lawrence Berkeley National Laboratory and University of California, Berkeley*

sized stars containing 10 or more times the mass of our sun. These stars live for millions of years, continually fusing hydrogen into progressively heavier elements. Once they have burned their insides to iron, which is essentially nuclear ash, fusion cannot continue. Without this outward pressure, the innermost core of the star collapses under the pull of gravity and compresses a millionfold in volume, transforming into an ultradense nugget called a neutron star, which packs a mass greater than that of the sun into a region no more than a few miles across. The enormous energy released in the free fall blows apart the rest of the star.

To get a sense of the energy involved in a typical supernova explosion, imagine that our sun burned its entire supply of hydrogen—enough fuel to sustain it for more than 10 billion years—within a few seconds. That enormous amount of energy is quantified by its own physical unit: one bethe (named after Nobel Prize winner Hans Bethe). When a supernova explodes, the star's interior temperature rises above five billion degrees Fahrenheit, driving a supersonic blast wave that leaves in its wake a mess of freshly fused heavy elements, such as silicon, calcium, iron, and radioactive isotopes of nickel, cobalt and titanium. In a matter of minutes, the star blows apart into a cloud of ash and radioactive debris, expelled at 20 million miles per hour, or a few percent the speed of light.

Our own sun is, fortunately, too small to ever go supernova, but if it did, the first indication on Earth would be a brief flash of intense x-rays that would kill all life on the planet. Within a few minutes the solar debris cloud would double in size and become about 1,000 times brighter than the sun. After a few hours the cloud would engulf Earth, and a day later it would swallow Jupiter and Saturn. After a few weeks the solar ashes would spread across the entire solar system. By this time, the debris cloud would finally become translucent, and the bottled-up light would flood out, reaching a peak brightness of about one billion solar luminosities before fading away.

Astronomers almost never catch the brief x-ray blast of a supernova explosion itself, and only rarely can we dig up an archived picture of the original star before it exploded. What we typically see is only the aftermath: that giant cloud of expanding, radioactive debris that glows visibly for weeks or longer. By examining the ashes, we try to piece together a story of what type of star was destroyed and why.

STRANGELY BRIGHT

AMONG THE ZOO of weird supernovae recently discovered, perhaps the most dramatic are hyperenergetic explosions—what I will call ultranovae—that are more than 100 times as luminous as ordinary supernovae. They are the brightest and most distant supernovae ever discovered, visible most of the way across the observable universe. Such events are extremely rare; perhaps one goes off for every 1,000 ordinary supernovae. Astronomers have no conclusive evidence to explain why these blasts are so bright, but there are three leading theories. One of them may explain most or all of the ultranovae we see, but it is more likely that all three scenarios occur with some frequency.

PARTICLE-PAIR SUPERNOVAE. Naturally, many try to associate ultranovae with extremely massive stars. Theory suggests that very large stars are actually rather delicate characters, susceptible to a variety of instabilities. In particular, stars between 150 and 250 solar masses may become so hot in their cores that they generate a flurry of matter-antimatter particle pairs (namely, electrons and positrons). Producing these particles costs energy, which saps a star's outward pressure and causes its core, still loaded with combustible nuclear fuel, to fall in. The result would be disastrous. The compression of the core would accelerate nuclear fusion out of control, burning almost everything in sight. The sudden energy release—as much as 100 bethes' worth—would reverse the collapse and explode the star completely. Nothing would be left behind.

These most giant of nuclear explosions would produce debris clouds 1,000 times more radioactive than those of ordinary supernovae. Because the clouds are also thought to be extremely massive and opaque, the light would take a year or longer to diffuse out. We therefore expect the aftermath of these explosions to be extremely bright and long-lasting. A few of the recently discovered ultranovae have just these properties, leading some astronomers to claim that we have witnessed a giant star killed by an infestation of microscopic particle pairs. Others disagree, arguing that the data are better explained with different theories. Future observations of such bright and long-lived events will, it is hoped, better reveal the composition and speed of the stellar debris cloud and tell us whether this scenario truly does take place.

FALSE ALARM SUPERNOVAE. An alternative idea to explain ultranovae is that they originate in stars slightly lower in mass (around 70 to 150 solar masses). These stars are thought to be subject to similar instabilities as their more massive brethren, but the conditions are often not as severe; after the star begins to crumple and ignite excess burning, it may rebound, reexpand and halt the nuclear reactions before they run out of control, recovering to live another day. In the process of regaining its balance, however, the star will likely blow off a good chunk of its outer layers, producing a supernova "imposter"—an outburst that resembles a dim supernova but in reality is just a near-death experience.

Stars that are in this mass range may go through several of these hiccups, each time losing a bit more matter, until they finally exhaust their nuclear fuel and explode like ordinary supernovae. When such a star finally does die, it will expel debris into an environment that is polluted with shells of material from previous outbursts. The violent collision of the supernova debris cloud with these shells should produce extremely bright fireworks that could explain some of the ultranovae.

Automated surveys have recently recorded the manic last years in the life of a massive star. In 2009 astronomers noted what appeared to be a fairly ordinary, if dim, supernova. Named SN2009ip, it faded away in a few weeks and was largely forgotten. One year later, to everyone's surprise, another dim "supernova" was observed in the exact same location. Apparently the star was not dead yet. In 2012 astronomers saw a third outburst and then, a month later, a very luminous one.

Some scientists believe that the penultimate burst was the true death of the star while the final, most luminous flare resulted from the supernova debris cloud ramming into material from the previous near-death gasps. Others think that the star is still alive and will continue to entertain us with further outbursts. It will take a few years for the dust to clear, but for now we have seen the kind of violent instability we think makes up the end of life for some massive stars.

MAGNETIC SUPERNOVAE. Finally, an alternative line of thinking on ultranovae argues that their excessive brightness has less to do with extreme mass and more to do with extreme rotation. Stars that start off with more than 10 solar masses most likely produce ordinary supernovae that form neutron stars when they die. If such a star was initially rotating rapidly, the collapse might spin up the neutron star to extreme speeds, like a twirling figure skater who brings his or her arms in to accelerate. In principle, a neutron star can spin as rapidly as 1,000 rotations a second—much faster, and the star would be torn apart by centrifugal forces. The kinetic energy stored in such a massive, spinning top is enormous—up to 10 bethes.

How can this spin energy be tapped to power an ultranova? Neutron stars have immense magnetic fields that may transport the energy. To understand how, imagine spinning a refrigerator magnet in your palm. As you do so, you twist up the magnetic field surrounding it. Although you cannot see or feel it, a bit of your expended energy is carried off into space in the form of electromagnetic ripples. We think the same process occurs, on a much larger scale, around neutron stars. The most visually captivating example is the Crab nebula, the remains of a supernova reported by Chinese astronomers in A.D. 1054. Today the light we see from the nebula is powered by a spinning neutron star that generates a whirlpool of magnetized plasma. Over a period of 1,000 years the twisted-up magnetic field has extracted the neutron star spin energy and heated the surrounding gas, powering the beautiful display.

About five years ago my colleague Lars Bildsten of the University of California, Santa Barbara, and I suggested that a souped-up version of this process may explain the high luminosity of ultranovae. The neutron star would need to host magnetic fields 100 to 1,000 times stronger than the one in the Crab nebula and spin near the breakup speed limit. For such a star, nearly the entire spin energy could drain within a month, causing the supernova debris cloud to shine a million times more brightly than the Crab nebula. Although the numbers sound extreme, we have already observed some neutron stars with comparable magnetic fields (though none yet in the supernova stage). They are called magnetars, and they harbor the strongest known magnetic fields in the universe. Ultranovae may therefore sometimes signal the birth and prompt spinning down of a rapidly rotating magnetar.

Supernova Zoo

Supernova explosions, which signal the deaths of stars, come in a much wider variety than scientists thought. Recent observations have revealed supernovae that are 100 times brighter than usual, as well as underperforming blasts that are 1/100th as bright as the norm. Theorists have several ideas about what types of stars and situations give rise to some of these unusual eruptions.

Ordinary
In a typical supernova, the core of a star weighing 10 or more times the mass of our sun collapses into a dense remnant called a neutron star, and the outer layers explode in a supersonic blast wave.

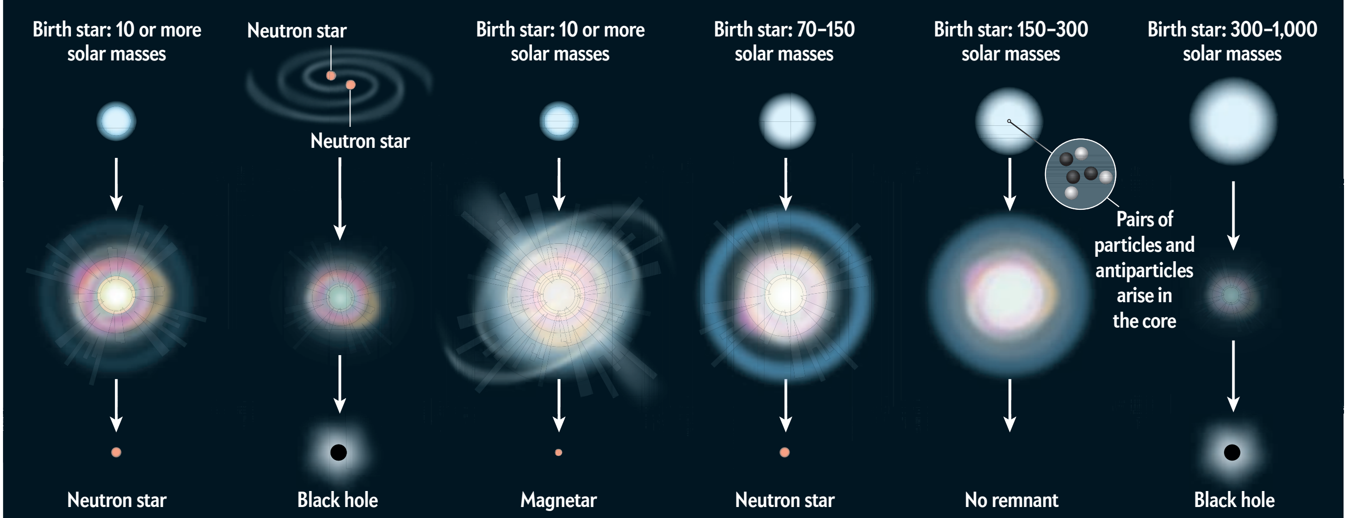
Neutron Star Collision
When two neutron stars crash together, scientists think most of their mass will create a black hole, but a small part may escape to power an under-bright "kilonova."

Magnetar
The collapse of a rapidly rotating star may produce a highly magnetized neutron star, called a magnetar, that taps the spin energy to power an ultraluminous supernova.

False Alarm
A star may begin to go supernova but regain its balance, blowing off just some of its outer layers. When this star finally does explode, the debris will hit the previously shed layers, creating an ultrabright flash.

Particle Pair
The hot cores of very massive stars may give rise to pairs of matter and antimatter particles that precipitate a premature blast. The energy would destroy the star and prevent a black hole from forming.

Complete Collapse
The most massive stars might produce a whimper rather than a bang because their extreme gravity would pull nearly their whole mass into something denser than a neutron star: a black hole.



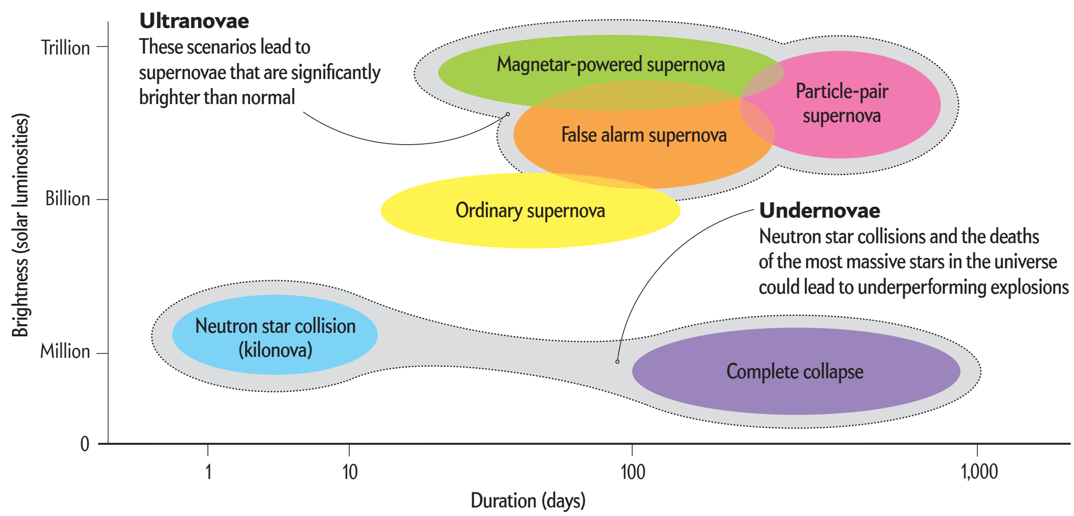


Illustration by Jen Christiansen

CRAB NEBULA: This supernova remnant is powered by a spinning neutron star that injects a whirlpool of magnetized plasma (*visible in blue*).

COURTESY OF NASA/CXC/SAO/F. SEWARD (*composite*); COURTESY OF NASA/ESA/ASU/J. HESTER AND A. LOLL (*optical*); NASA/JPL-CALTECH/UNIVERSITY OF MINNESOTA/R. GEHRZ (*infrared*)

UNEXPECTEDLY DIM

ON THE OPPOSITE END of the spectrum from ultranovae, astronomers have also recently discovered the strange phenomenon of underperforming supernovae. Wide-field surveys have found peculiar supernovae that are 100 times as dim as ordinary events. Scientists debate what causes these weak outbursts but suspect some are, surprisingly, the muffled last gasps of the most massive stars to have ever lived.

FAILED SUPERNOVAE. It is unclear just how massive a star can get, but conceivably some may be as large as 300 to 1,000 times the mass of the sun (even larger than the very massive stars we think might explode because of particle pairs). One might expect these mammoths to produce the most spectacular supernova explosions of all. Actually they are probably duds. The gravity of such a star is so strong that once it becomes unstable, total collapse is inevitable. The infall should eventually tear a hole in spacetime itself, forming something denser than a neutron star: a black hole.

Theoretical models show that the bulk of the star will be swallowed by the black hole and suddenly disappear from sight. This hypothetical nonevent has been called an unnova. Automated surveys are looking for unnovae in a backward way: searching not for a sudden light in the sky but for a bright star that goes lights out in an instant.

Although they fail to make a bang, some of these black hole–forming stars may at least manage a whisper. The cores of cer-

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tain giant stars are surrounded by a loose, puffy halo of hydrogen gas. As the bulk of such a star gets sucked below the black hole horizon, the halo of gas may heat up and blow away, leading to a faint glow. The death of a very big star would then produce, ironically, a remarkably weak and dim supernova.

COLLIDING NEUTRON STARS. Another type of underluminous eruption might come from a very different kind of extreme event: the collision of two neutron stars. Massive stars are frequently born as orbiting pairs. These stars will go supernova one after the other, and if the pair is not flung apart, what remains is a binary system of two neutron stars (or a neutron star and a black hole or two black holes). Over time, the two compact objects should spiral in closer and closer, ultimately colliding and coalescing into a larger black hole. This process was recently confirmed by the discovery of gravitational waves produced in the merger of two black holes. When neutron stars meld, calculations suggest that the extreme gravitational forces (about 10 billion times the pull of Earth's gravity on our bodies) are strong enough to strip off about 1 percent of the stars' skin and fling it out into space (the remaining 99 percent goes into the black hole).

This small bit of material that escapes the black hole most likely is peculiar stuff—a vaporized sea of disassociated particles, mostly neutrons, along with some protons and electrons. As the gas decompresses, the particles should begin to bind together into heavier nuclei. The protons will repulse one another because of their positive electric charge, but the neutrons have no charge and will attach to other particles more easily. By progressive addition of neutrons, the nuclei should grow heavier and heavier, producing a shower of elements across the lower half of the periodic table, such as gold, platinum and mercury, mixed into a pool of assorted radioactive waste, including uranium and thorium. Neutron star collisions are one of the few places in the universe scientists think these heavy elements can be formed.

The abundance of radioactive material should cause the debris cloud to glow like a supernova. But because of the relatively small mass involved (less than 1 percent of that found in a supernova), we expect the light to be about 100 times as dim as an ordinary supernova and to last for only a few days. Recent theoretical work I did with my graduate student Jennifer Barnes at the University of California, Berkeley, suggests that the peculiar composition of heavy metals in such clouds should give the glow a distinctive color, either a deep-red or infrared hue. The phenomenon has been called a kilonova.

Lately astronomers may have, for the first time, seen this radioactive red "smoke" from a neutron star collision. In June 2013 a brief burst of gamma rays alerted astronomers to a possible nearby neutron star merger. They pointed the Hubble Space Telescope at the site and caught a brief infrared glow. A few weeks later it was gone. The data are scarce but consistent with theoretical predictions of what a kilonova should look like. If this identification is correct, it is the first time we have directly witnessed the production of heavy, precious metals. We would like to observe more such events to better determine the amount of metals these explosions synthesize and whether they can account for all, or only part, of the abundance of gold, platinum and other heavy elements in the universe.

CHAOTIC COSMOS

OUR STUDY of the dynamic universe has just begun. Within a decade or so new automated telescopes such as the Zwicky Transient Facility coming online near San Diego, the Large Synoptic Survey Telescope being built in Chile and the Wide-Field Infrared Survey Telescope that NASA plans to launch into space will be able to scan most of the sky every few nights, discovering hundreds of times as many supernovae as we currently do. Meanwhile modern supercomputers are becoming capable of carrying out detailed three-dimensional simulations of these events, allowing us to visualize what may go on deep in the cores of exploding stars.

Data gathered in the coming years will challenge our theories about the many types of stellar deaths. Each scenario described here is physically plausible but unproved. With more observations of unusual supernovae, we hope to pin down which of these explosive possibilities are, in fact, realized in nature. Most likely, the universe will turn out to be stranger than we have imagined, revealing even more exotic phenomena than we have dreamed up so far.

The death of a very big star would produce a remarkably dim supernova.

Ultimately we will also be able to tell a richer narrative of the stuff that makes up our bodies and the world around us. The gold ring on your finger, for example, has a history that goes back beyond the time of your ancestors. That material probably first floated in the iron furnace of a massive star that faltered, collapsed and compressed into a dense neutron star. Much later, after maybe a billion years, the neutron star might have crashed into another compact star, spewing a cloud of radioactive waste out into space. That cloud, rushing at 60 million miles per hour, would have traveled more than 1,000 light-years across the galaxy, mixing with other gases along the way, until it eventually settled into the crust of planet Earth. Some time later people dug up that stellar rubble, shaped a ring and began to tell their own stories. SA

MORE TO EXPLORE

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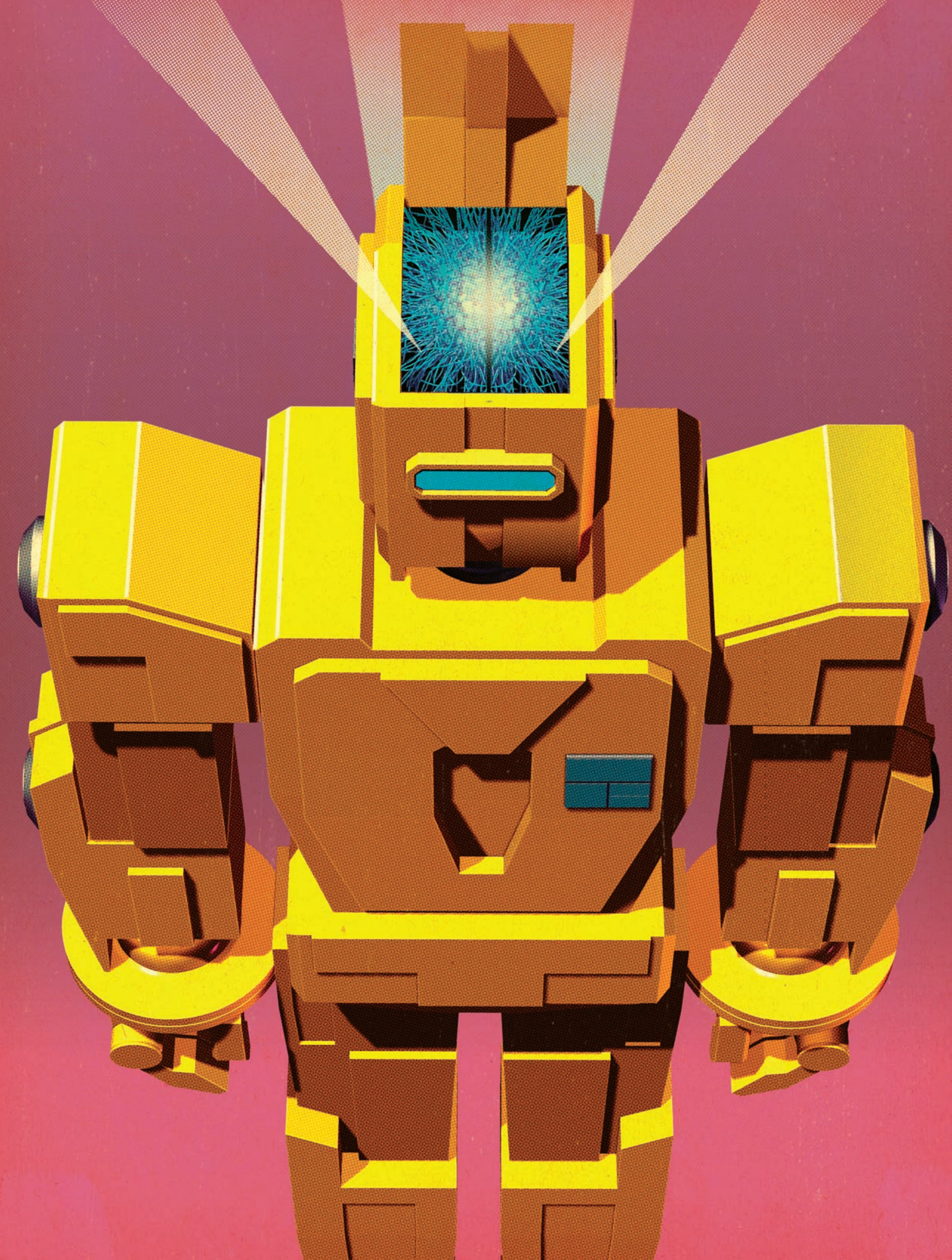


THE RISE OF AI

AI SPECIAL REPORT

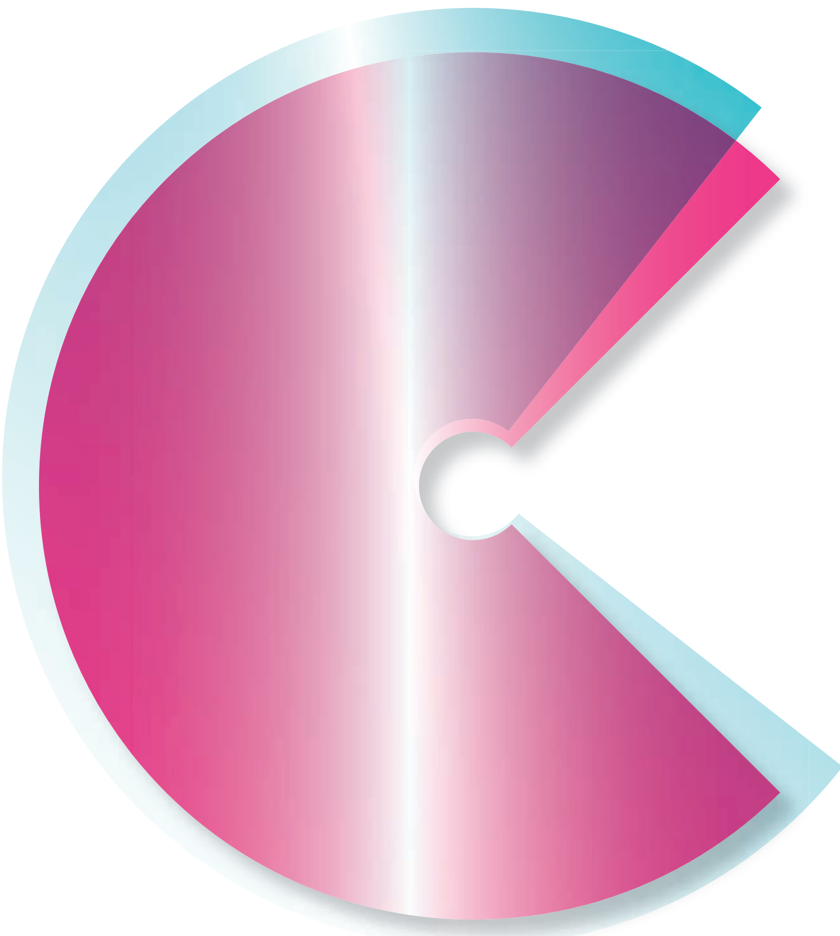
The promise of driverless cars and software that teaches itself new skills has sparked a revival of artificial intelligence—and, with it, fears that our machines may one day turn against us

Illustrations by Tavis Coburn

AI SPECIAL REPORT

COMPUTER SCIENCE

MACHINES WHO LEARN



After decades of disappointment, artificial intelligence is finally catching up to its early promise, thanks to a powerful technique called deep learning

By Yoshua Bengio

OMPUTERS GENERATED A GREAT DEAL of excitement in the 1950s when they began to beat humans at checkers and to prove math theorems. In the 1960s the hope grew that scientists might soon be able to replicate the human brain in hardware and software and that "artificial intelligence" would soon match human performance on any task. In 1967 Marvin Minsky of the Massachusetts Institute of Technology, who died earlier this year, proclaimed that the challenge of AI would be solved within a generation.

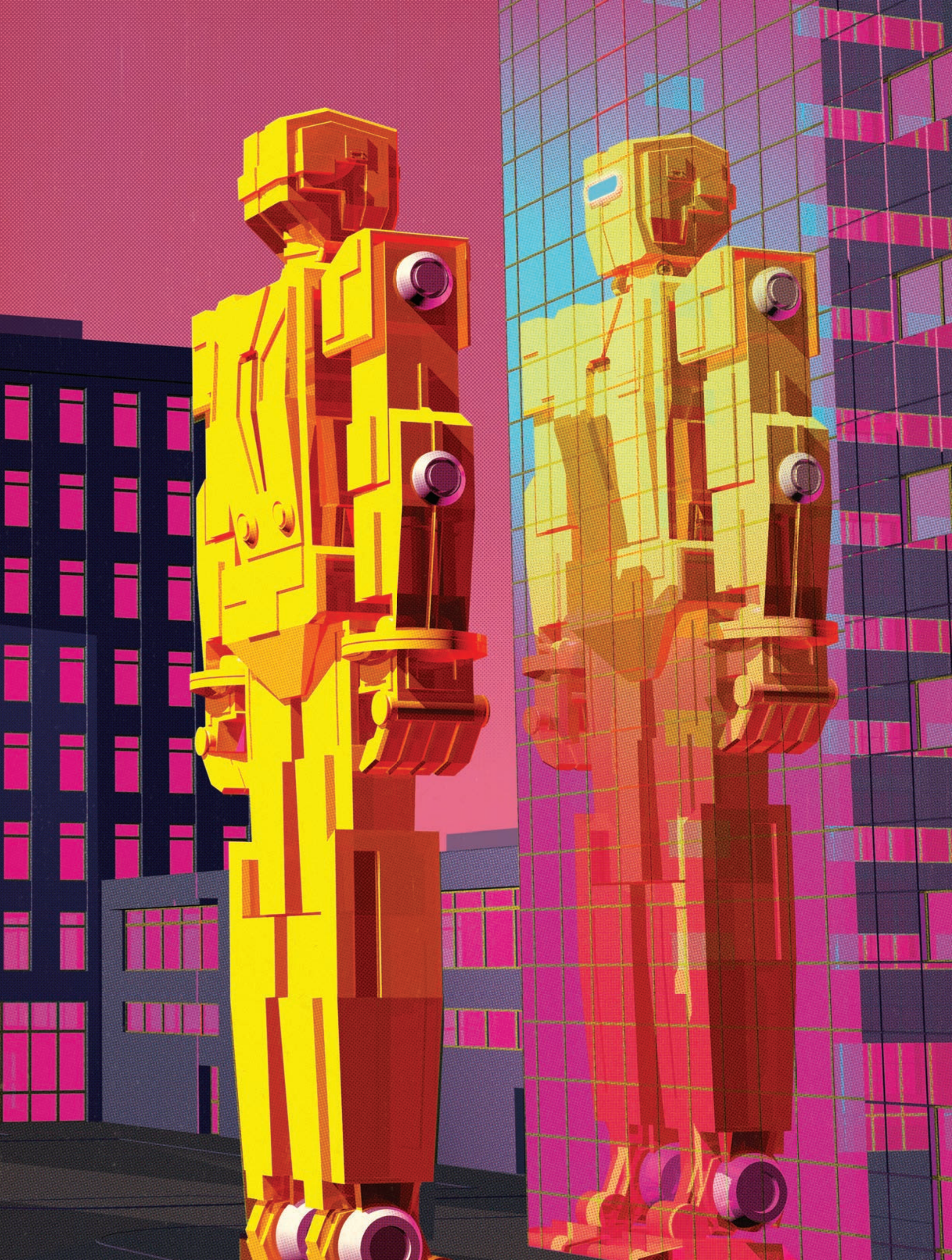
IN BRIEF

Artificial intelligence started as a field of serious study in the mid-1950s. At the time, investigators expected to emulate human intelligence within the span of an academic career.

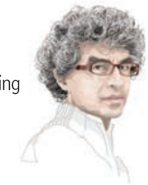
Hopes were dashed when it became clear that the algorithms and computing power of that period were simply not up to the task. Some skeptics even wrote off the endeavor as pure hubris.

A revival took place during the past few years as software patterned roughly after networks of neurons in the brain demonstrated that AI's early promise might yet be realized.

Deep learning—a technique that uses complex neural networks—has the ability to learn abstract concepts and already approaches human-level performance on some tasks.



Yoshua Bengio is a professor of computer science at the University of Montreal and one of the pioneers in developing the deep-learning methods that have sparked the current revival of artificial intelligence.



That optimism, of course, turned out to be premature. Software designed to help physicians make better diagnoses and networks modeled after the human brain for recognizing the contents of photographs failed to live up to their initial hype. The algorithms of those early years lacked sophistication and needed more data than were available at the time. Computer processing was also too tepid to power machines that could perform the massive calculations needed to approximate something approaching the intricacies of human thought.

By the mid-2000s the dream of building machines with human-level intelligence had almost disappeared in the scientific community. At the time, even the term "AI" seemed to leave the domain of serious science. Scientists and writers describe the dashed hopes of the period from the 1970s until the mid-2000s as a series of "AI winters."

What a difference a decade makes. Beginning in 2005, AI's outlook changed spectacularly. That was when deep learning, an approach to building intelligent machines that drew inspiration from brain science, began to come into its own. In recent years deep learning has become a singular force propelling AI research forward. Major information technology companies are now pouring billions of dollars into its development.

Deep learning refers to the simulation of networks of neurons that gradually "learn" to recognize images, understand speech or even make decisions on their own. The technique relies on so-called artificial neural networks—a core element of current AI research. Artificial neural networks do not mimic precisely how actual neurons work. Instead they are based on general mathematical principles that allow them to learn from examples to recognize people or objects in a photograph or to translate the world's major languages.

The technology of deep learning has transformed AI research, reviving lost ambitions for computer vision, speech recognition, natural-language processing and robotics. The first products rolled out in 2012 for understanding speech—you may be familiar with Google Now. And shortly afterward came applications for identifying the contents of an image, a feature now incorporated into the Google Photos search engine.

Anyone frustrated by clunky automated telephone menus can appreciate the dramatic advantages of using a better personal assistant on a smartphone. And for those who remember how poor object recognition was just a few years ago—software that might mistake an inanimate object for an animal—strides in computer vision have been incredible: we now have computers that, under certain conditions, can recognize a cat, a rock or faces in images almost as well as humans. AI software, in fact, has now become a familiar fixture in the lives of millions of smartphone users. Personally, I rarely type messages anymore. I often just speak to my phone, and sometimes it even answers back.

These advances have suddenly opened the door to further commercialization of the technology, and the excitement only continues to grow. Companies compete fiercely for talent, and Ph.D.s specializing in deep learning are a rare commodity that is in extremely high demand. Many university professors with expertise in this area—by some counts, the majority—have been pulled from academia to industry and furnished with well-appointed research facilities and ample compensation packages.

Working through the challenges of deep learning has led to stunning successes. The triumph of a neural network over top-ranked player Lee Se-dol at the game of Go received prominent headlines. Applications are already expanding to encompass other fields of human expertise—and it is not all games. A newly developed deep-learning algorithm is purported to diagnose heart failure from magnetic resonance imaging as well as a cardiologist.

INTELLIGENCE, KNOWLEDGE AND LEARNING

WHY DID AI HIT so many roadblocks in previous decades? The reason is that most of the knowledge we have of the world around us is not formalized in written language as a set of explicit tasks—a necessity for writing any computer program. That is why we have not been able to directly program a computer to do many of the things that we humans do so easily—be it understanding speech, images or language or driving a car. Attempts to do so—organizing sets of facts in elaborate databases to imbue computers with a facsimile of intelligence—have met with scant success.

That is where deep learning comes in. It is part of the broader AI discipline known as machine learning, which is based on principles used to train intelligent computing systems—and to ultimately let machines teach themselves. One of these tenets relates to what a human or machine considers a "good" decision. For animals, evolutionary principles dictate decisions should be made that lead to behaviors that optimize chances of survival and reproduction. In human societies, a good decision might include social interactions that bring status or a sense of well-being. For a machine, such as a self-driving car, though, the quality of decision making depends on how closely the autonomous vehicle imitates the behaviors of competent human drivers.

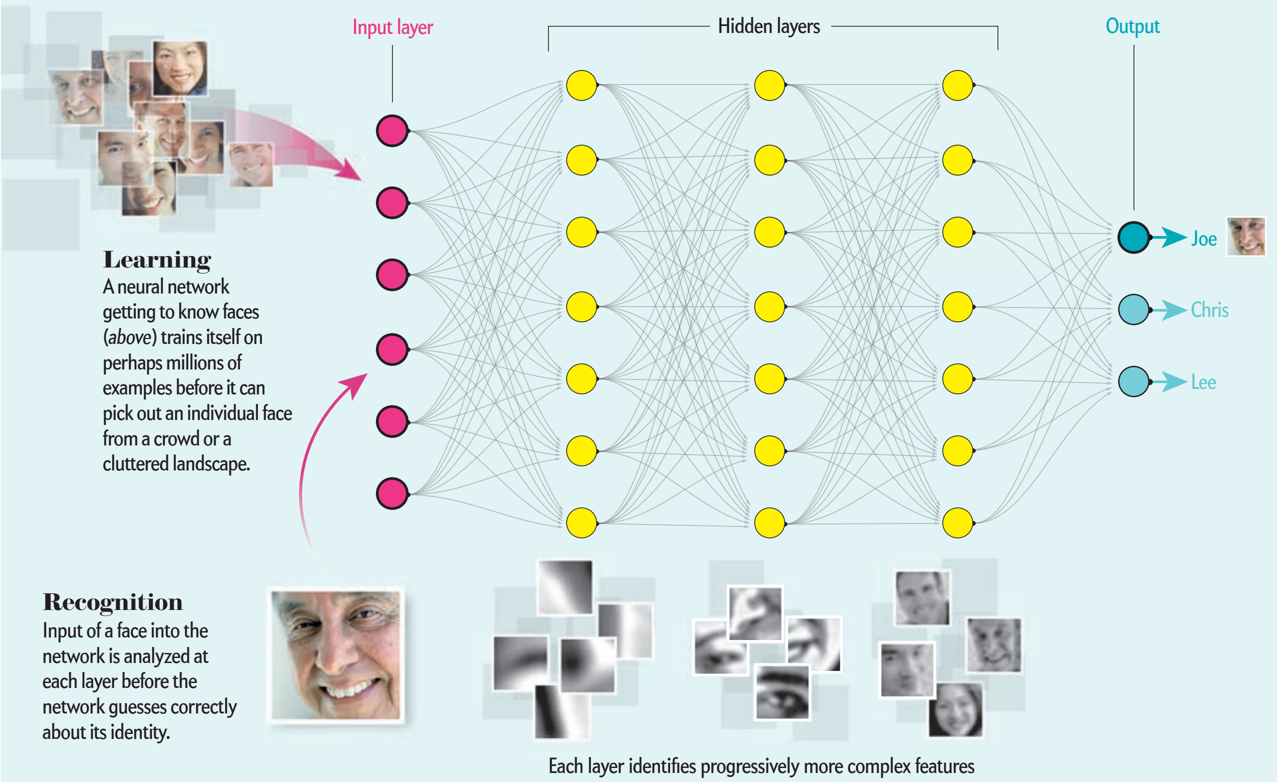
The knowledge needed to make a good decision in a particular context is not necessarily obvious in a way that can be translated into computer code. A mouse, for instance, has knowledge of its surroundings and an innate sense of where to sniff and how to move its legs, find food or mates, and avoid predators. No programmer would be capable of specifying a step-by-step set of instructions to produce these behaviors. Yet that knowledge is encoded in the rodent's brain.

Before creating computers that can train themselves, computer scientists needed to answer such fundamental questions as how humans acquire knowledge. Some knowledge is innate, but most is learned from experience. What we know intuitively cannot be turned into a clear sequence of steps for a computer to execute but can often be learned from examples and practice. Since the 1950s researchers have looked for and tried to refine general principles that allow animals or humans—or even machines, for that matter—to acquire knowledge through experience. Machine learning aims to establish procedures, called learning algorithms, that allow a machine to learn from examples presented to it.

Brainy Networks That Only Get Smarter

Connections from one neuron to the next in the brain's cortex have inspired the creation of algorithms that mimic these intricate links. A neural network can be trained to recognize a face by first training on countless images. Once it has "learned" to categorize a face (versus a hand, for instance) and to detect individual faces, the network uses that knowledge to identify faces it has seen before, even if the image of the person is slightly different from the one it was trained on.

To recognize a face, the network sets about the task of analyzing the individual pixels of an image presented to it at the input layer. Then, at the next layer, it chooses geometric shapes distinctive to a particular face. Moving up the hierarchy, a middle layer detects eyes, a mouth and other features before a composite full-face image is discerned at a higher layer. At the output layer, the network makes a "guess" about whether the face is that of Joe or rather that of Chris or Lee.



Learning
A neural network getting to know faces (*above*) trains itself on perhaps millions of examples before it can pick out an individual face from a crowd or a cluttered landscape.

Recognition
Input of a face into the network is analyzed at each layer before the network guesses correctly about its identity.

The science of machine learning is largely experimental because no universal learning algorithm exists—none can enable the computer to learn every task it is given well. Any knowledge-acquisition algorithm needs to be tested on learning tasks and data specific to the situation at hand, whether it is recognizing a sunset or translating English into Urdu. There is no way to prove that it will be consistently better across the board for any given situation than all other algorithms.

AI researchers have fashioned a formal mathematical description of this principle—the "no free lunch" theorem—that demonstrates that no algorithm exists to address every real-world learning situation. Yet human behavior apparently contradicts this theorem. We appear to hold in our head fairly general learning abilities that allow us to master a multitude of tasks for which evolution did not prepare our ancestors: playing chess, building bridges or doing research in AI.

These capabilities suggest that human intelligence exploits general assumptions about the world that might serve as inspiration for creating machines with a form of general intelligence. For just this reason, developers of artificial neural networks have adopted the brain as a rough model for designing intelligent systems.

The brain's main units of computation are cells called neurons. Each neuron sends a signal to other neurons through tiny gaps between the cells known as synaptic clefts. The propensity of a neuron to send a signal across the gap—and the amplitude of that signal—is referred to as synaptic strength. As a neuron "learns," its synaptic strength grows, and it is more likely, when stimulated by an electrical impulse, to send messages along to its neighbors.

Brain science influenced the emergence of artificial neural networks that used software or hardware to create virtual neurons. Early researchers in this subfield of AI, known as connectionism, postulated that neural networks would be able to learn

PUNCHSTOCK (*faces*)

Graphic by Jen Christiansen

complex tasks by gradually altering the connections among neurons, so that patterns of neural activity would capture the content of its input, such as an image or a snippet of dialogue. As these networks would receive more examples, the learning process would continue by changing synaptic strengths among the connected neurons to achieve more accurate representations of, say, images of a sunset.

LESSONS ABOUT SUNSETS

THE CURRENT GENERATION of neural networks extends the pioneering work of connectionism. The networks gradually change numerical values for each synaptic connection, values representing the strength of that connection and thus how likely a neuron is to transmit a signal along to another neuron. An algorithm used by deep-learning networks changes these values ever so slightly each time it observes a new image. The values inch steadily closer toward ones that allow the neural network to make better predictions about the image's content.

For best results, current learning algorithms require close involvement by a human. Most of these algorithms use supervised learning in which each training example is accompanied by a human-crafted label about what is being learned—a picture of a sunset, say, is associated with a caption that says "sunset." In this instance, the goal of the supervised learning algorithm is to take a photograph as the input and produce, as an output, the name of a key object in the image. The mathematical process of transforming an input to an output is called a function. The numerical values, such as synaptic strengths, that produce this function correspond to a solution to the learning task.

Learning by rote to produce correct answers would be easy but somewhat useless. We want to teach the algorithm what a sunset is but then to have it recognize an image of any sunset, even one it has not been trained on. The ability to discern any sunset—in other words, to generalize learning beyond specific examples—is the main goal of any machine-learning algorithm. In fact, the quality of training of any network is evaluated by testing it using examples not previously seen. The difficulty of generalizing correctly to a new example arises because there is an almost infinite set of possible variations that still correspond to any category, such as a sunset.

To succeed in generalizing from having observed a multitude of examples, the learning algorithm used in deep-learning networks needs more than just the examples themselves. It also relies on hypotheses about the data and assumptions about what a possible solution to a particular problem might be. A typical hypothesis built into the software might postulate that if data inputs for a particular function are similar, the outputs should not radically change—altering a few pixels in an image of a cat should not usually transform the animal into a dog.

One type of neural network that incorporates hypotheses about images is called a convolutional neural network; it has become a key technology that has fueled the revival of AI. Convolutional neural networks used in deep learning have many layers of neurons organized in such a way as to make the output less sensitive to the main object in an image changing, such as when its position is moved slightly—a well-trained network may be able to recognize a face from different angles in separate photographs. The design of a convolutional network draws its inspiration from the multilayered structure of the visual cortex—the part of our brain that receives input from the eyes. The many layers of virtual neurons in a convolutional neural network are what makes a network "deep" and thus better able to learn about the world around it.

GOING DEEP

ON A PRACTICAL LEVEL, the advances that enabled deep learning came from specific innovations that emerged about 10 years ago, when interest in AI and neural networks had reached its lowest point in decades. A Canadian organization funded by the government and private donors, the Canadian Institute for Advanced Research (CIFAR), helped to rekindle the flame by sponsoring a program led by Geoffrey Hinton of the University of Toronto. The program also included Yann LeCun of New York University, Andrew Ng of Stanford University, Bruno Olshausen of the University of California, Berkeley, me and several others. Back then, negative attitudes toward this line of research made it difficult to publish and even to convince graduate students to work in this area, but a few of us had the strong sense that it was important to move ahead.

> The strong comeback for AI after a long and extended hiatus provides a lesson in the sociology of science, underscoring the need to put forward ideas that challenge the technological status quo.

Skepticism about neural networks at that time stemmed, in part, from the belief that training them was hopeless because of the challenges involved in optimizing how they behave. Optimization is a branch of mathematics that tries to find the configuration of a set of parameters to reach a mathematical objective. The parameters, in this case, are called synaptic weights and represent how strong a signal is being sent from one neuron to another.

The objective is to make predictions with the minimum number of errors. When the relation between parameters and an objective is simple enough—more precisely when the objective is a convex function of the parameters—the parameters can be gradually adjusted. This continues until they get as close as

possible to the values that produce the best possible choice, known as a global minimum—which corresponds to the lowest possible average prediction error made by the network.

In general, however, training a neural network is not so simple—and requires what is called a nonconvex optimization. This type of optimization poses a much greater challenge—and many researchers believed that the hurdle was insurmountable. The learning algorithm can get stuck in what is called a local minimum, in which it is unable to reduce the prediction error of the neural network by adjusting parameters slightly.

Only in the past year was the myth dispelled that neural networks were hard to train because of local minima. We found in our research that when a neural network is sufficiently large, the local minima problem is greatly reduced. Most local minima actually correspond to having learned knowledge at a level that almost matches the optimal value of the global minimum.

Although the theoretical problems of optimization could, in theory, be solved, building large networks with more than two or three layers had often failed. Beginning in 2005, CIFAR-supported efforts achieved breakthroughs that overcame these barriers. In 2006 we managed to train deeper neural networks, using a technique that proceeded layer by layer.

Later, in 2011, we found a better way to train even deeper networks—ones with more layers of virtual neurons—by altering the computations performed by each of these processing units, making them more like what biological neurons actually compute. We also discovered that injecting random noise into the signals transmitted among neurons during training, similar to what happens in the brain, made them better able to learn to correctly identify an image or sound.

Two crucial factors aided the success of deep-learning techniques. An immediate 10-fold increase in computing speed, thanks to the graphics-processing units initially designed for video games, allowed larger networks to be trained in a reasonable amount of time. Also fueling deep learning's growth was the availability of huge labeled data sets for which a learning algorithm can identify the correct answer—"cat," for example, when inspecting an image in which a cat is just one element.

Another reason for deep learning's recent success is its ability to learn to perform a sequence of computations that construct or analyze, step by step, an image, a sound or other data. The depth of the network is the number of such steps. Many visual- or auditory-recognition tasks in which AI excels require the many layers of a deep network. In recent theoretical and experimental studies, in fact, we have shown that carrying out some of these mathematical operations cannot be accomplished efficiently without sufficiently deep networks.

Each layer in a deep neural network transforms its input and produces an output that is sent to the next layer. The network represents more abstract concepts at its deeper layers [*see box on page 49*], which are more remote from the initial raw sensory input. Experiments show that artificial neurons in deeper layers in the network tend to correspond to more abstract semantic concepts: a visual object such as a desk, for instance. Recognition of the image of the desk might emerge from the processing of neurons at a deeper layer even though the concept of "desk" was not among the category labels on which the network was trained. And the concept of a desk might itself only be an intermediate step toward creating a still more abstract concept at a still higher layer that might be categorized by the network as an "office scene."

BEYOND PATTERN RECOGNITION

UNTIL RECENTLY, artificial neural networks distinguished themselves in large part for their ability to carry out tasks such as recognizing patterns in static images. But another type of neural network is also making its mark—specifically, for events that unfold over time. Recurrent neural networks have demonstrated the capacity to correctly perform a sequence of computations, typically for speech, video and other data. Sequential data are made up of units—whether a phoneme or a whole word—that follow one another sequentially. The way recurrent neural networks process their inputs bears a resemblance to how the brain works. Signals that course among neurons change constantly as inputs from the senses are processed. This internal neural state changes in a way that depends on the current input to the brain from its surroundings before issuing a sequence of commands that result in body movements directed at achieving a specific goal.

Recurrent networks can predict what the next word in a sentence will be, and this can be used to generate new sequences of words, one at a time. They can also take on more sophisticated tasks. After "reading" all the words in a sentence, the network can guess at the meaning of the entire sentence. A separate recurrent network can then use the semantic processing of the first network to translate the sentence into another language.

Research on recurrent neural networks had its own lull in the late 1990s and early 2000s. My theoretical work suggested that they would run into difficulty learning to retrieve information from the far past—the earliest elements in the sequence being processed. Think of trying to recite the words from the first sentences of a book verbatim when you have just reached the last page. But several advances have lessened some of these problems by enabling such networks to learn to store information so that it persists for an extended time. The neural networks can use a computer's temporary memory to process multiple, dispersed pieces of information, such as ideas contained in different sentences spread across a document.

The strong comeback for deep neural networks after the long AI winter is not just a technological triumph. It also provides a lesson in the sociology of science. In particular, it underscores the need to support ideas that challenge the technological status quo and to encourage a diverse research portfolio that backs disciplines that temporarily fall out of favor. SA

MORE TO EXPLORE

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TRANSPORTATION

THE TRUTH ABOUT "SELF-DRIVING" CARS

AI SPECIAL REPORT

They are coming, but not the way you may have been led to think

By Steven E. Shladover

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祝大家阅读愉快！

Steven E. Shladover helped to create the California Partners for Advanced Transportation Technology (PATH) program at the Institute of Transportation Studies at the University of California, Berkeley, in the 1980s. He is a mechanical engineer by training, with bachelor's, master's and doctoral degrees from the Massachusetts Institute of Technology.

SOON ELECTRONIC CHAUFFEURS WILL TAKE US WHEREVER WE WANT to go, whenever we want, in complete safety—as long as we do not need to make any left turns across traffic. Changing road surfaces are a problem, too. So are snow and ice. It will be crucial to avoid traffic cops, crossing guards and emergency vehicles. And in an urban environment where pedestrians are likely to run out in front of the car, we should probably just walk or take the subway.

All these simple, everyday encounters for human drivers pose enormous problems for computers that will take time, money and effort to solve. Yet much of the public is becoming convinced that fully automated vehicles are just around the corner.

What created this disconnect? Part of the problem is terminology. The popular media applies the descriptors "autonomous," "driverless" and "self-driving" indiscriminately to technologies that are very different from one another, blurring important distinctions. And the automotive industry has not helped clarify matters. Marketers working for vehicle manufacturers, equipment suppliers and technology companies carefully compose publicity materials to support a wide range of interpretations about the amount of driving their products automate. Journalists who cover the field have an incentive to adopt the most optimistic forecasts—they are simply more exciting. The result of this feedback loop is a spiral of increasingly unrealistic expectations.

This confusion is unfortunate because automated driving is coming, and it could save lives, reduce pollution and conserve fuel. But it will not happen in quite the way you have been told.

DEFINING AUTOMATED DRIVING

DRIVING IS A MUCH MORE COMPLEX ACTIVITY than most people appreciate. It involves a broad range of skills and actions, some of which are easier to automate than others. Maintaining speed on an open road is simple, which is why conventional cruise-control systems have been doing it automatically for decades. As technology has advanced, engineers have been able to automate additional driving subtasks. Widely available adaptive cruise-control systems now maintain proper speed and spacing behind other vehicles. Lane-keeping systems, such as those in new models from Mercedes-Benz and Infiniti, use cameras, sensors and steering control to keep a vehicle centered in its lane. Cars are pretty smart these days. Yet it is an enormous leap from such systems to fully automated driving.

A five-level taxonomy defined by SAE International (formerly

IN BRIEF

The auto industry and the press have oversold the automated car. Simple road encounters pose huge challenges for computers, and robotic chauffeurs remain decades away.

Automated driving systems that rely on humans for backup are particularly problematic. Yet in the next decade we will see automatic-driving systems that are limited to specific conditions and applications.

Automatic parking valets, low-speed campus shuttles, closely spaced platoons of heavy trucks and automatic freeway-control systems for use in dedicated lanes are all feasible and perhaps inevitable.

TAXONOMY

The Ladder of Automation

The automotive industry and the media have made a mess of the terminology used to talk about automated driverless systems. The terms "autonomous," "driverless" and "self-driving" obscure more than they illuminate. To clear things up, SAE International wrote definitions, paraphrased here, for different levels of automation and arranged them on a ladder of decreasing reliance on the driver. The hierarchy reveals some surprises. For example, level-four automation is potentially more tractable than level three. Level-five automated systems—electronic chauffeurs that can handle any driving condition with no human input—are decades away.

	Human Driver Monitors Environment			System Monitors Environment		
	0 No Automation	**1** Driver Assistance	**2** Partial Automation	**3** Conditional Automation	**4** High Automation	**5** Full Automation
	The absence of any assistive features such as adaptive cruise control.	Systems that help drivers maintain speed or stay in lane but leave the driver in control.	The combination of automatic speed and steering control—for example, cruise control and lane keeping.	Automated systems that drive and monitor the environment but rely on a human driver for backup.	Automated systems that do everything—no human backup required—but only in limited circumstances.	The true electronic chauffeur: retains full vehicle control, needs no human backup and drives in all conditions.
Who steers, accelerates and decelerates	Human driver	Human driver and system	System	System	System	System
Who monitors the driving environment	Human driver	Human driver	Human driver	System	System	System
Who takes control when something goes wrong	Human driver	Human driver	Human driver	Human driver	System	System
How much driving, overall, is assisted or automated	None	Some driving modes	Some driving modes	Some driving modes	Some driving modes	All driving modes

SOURCE: SAE INTERNATIONAL (WWW.SAE.ORG/MISC/PDFS/AUTOMATED_DRIVING.PDF); FOR DOCUMENTATION, INCLUDING ORIGINAL DEFINITIONS IN THEIR ENTIRETY, SEE *TAXONOMY AND DEFINITIONS FOR TERMS RELATED TO ON-ROAD MOTOR VEHICLE AUTOMATED DRIVING SYSTEMS.* SAE INTERNATIONAL, JANUARY 2014

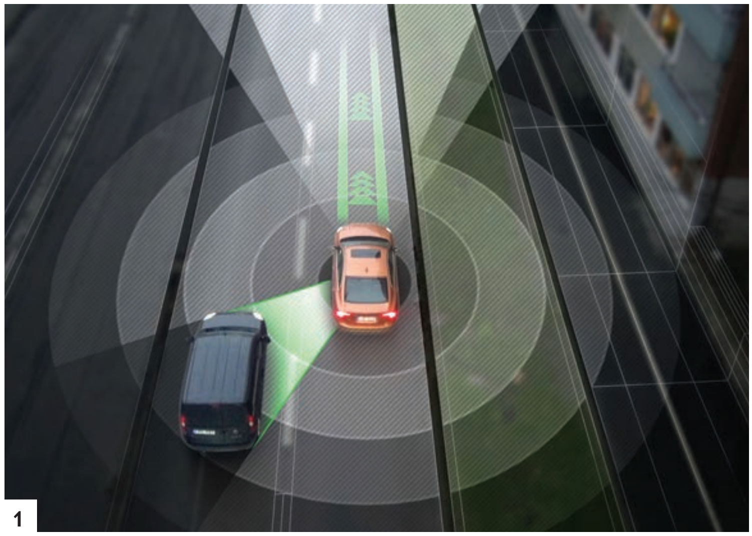
the Society of Automotive Engineers) is useful for clarifying our thinking about automated driving. The first three rungs on this ladder of increasing automation (excluding level zero, for no automation) are occupied by technologies that rely on humans for emergency backup. Adaptive cruise control, lane-keeping systems, and the like belong to level one. Level-two systems combine the functions of level-one technologies—the lateral and longitudinal controls of lane-keeping and adaptive cruise-control systems, for example—to automate more complex driving tasks. This is as far as commercially available vehicle automation goes today. Level-three systems would allow drivers to turn on autopilot in specific scenarios, such as freeway traffic jams.

The next two levels are profoundly different in that they operate entirely without human assistance. Level-four (high-auto-

Illustrations by Nigel Holmes (icons)

mation) systems would handle all driving subtasks, but they would operate only in strictly defined scenarios—in enclosed parking garages, for example, or in dedicated lanes on the freeway. At the top of the ladder is level five—the fully automated car. Presumably, this is what many people have in mind when they hear someone such as Nissan CEO Carlos Ghosn confidently proclaim that automated cars will be on the road by 2020.

The truth is that no one expects level-five automation systems to be on the market by then. In all likelihood, they are a long way off. Level-three systems might be just as remote. But level four? Look for it within the next decade. To understand this confusing state of affairs, we have to talk about software.



1

2

NEXT YEAR Volvo Cars will field-test 100 vehicles equipped with systems that automate driving on special stretches of freeway (*1* and *2*). Volvos have also been used in European road-train tests (*3*).

COURTESY OF VOLVO CAR GROUP (1–3)

SOFTWARE NIGHTMARE

DESPITE THE POPULAR PERCEPTION, human drivers are remarkably capable of avoiding serious crashes. Based on the total U.S. traffic safety statistics for 2011, fatal crashes occurred about once for every 3.3 million hours of driving; crashes that resulted in injury happened approximately once for every 64,000 hours of driving. These numbers set an important safety target for automated driving systems, which should, at minimum, be no less safe than human drivers. Reaching this level of reliability will require vastly more development than automation enthusiasts want to admit.

Think about how often your laptop freezes up. If that software were responsible for driving a car, the "blue screen of death" would become more than a figure of speech. A delayed software response of as little as one tenth of a second is likely to be hazardous in traffic. Software for automated driving must therefore be designed and developed to dramatically different standards from anything currently found in consumer devices.

Achieving these standards will be profoundly difficult and require basic breakthroughs in software engineering and signal processing. Engineers need new methods for designing software that can be proved correct and safe even in complex and rapidly changing conditions. Formal methods for analyzing every possible failure mode for a piece of code before it is written exist—think of them as mathematical proofs for computer programs—but only for very simple applications. Scientists are only beginning to think about how to scale up these kinds of tests to validate the incredibly complex code required to control a fully automated vehicle.

Once that code has been written, software engineers will need new methods for debugging and verifying it. Existing methods are too cumbersome and costly for the job. To put this in perspective, consider that half of the cost of a new commercial or military aircraft goes toward software verification and validation. The software on aircraft is actually much *less* complex than what will be needed for automated road vehicles. An engineer can design an aircraft autopilot system knowing that it will rarely, if ever, have to deal with more than one or two other aircraft in its vicinity. It does not need to know the velocity and location of those aircraft with incredible precision, because they are far enough apart that they have time to act. Decisions must be made on the order of tens of seconds. An automated road vehicle will have to track dozens of other vehicles and obstacles and make decisions within fractions of a second. The code required will be orders of magnitude more complex than what it takes to fly an airplane.

Once the code is validated, manufacturers will need ways to "prove" the safety of a complete automated driving system to the satisfaction of company risk-management officers, insurance firms, safety advocates, regulators and, of course, potential customers. The kind of formal "acceptance tests" used today are completely impractical for this purpose. Testers would have to put hundreds of millions, if not billions, of miles on a vehicle to ensure that they have subjected it in a statistically significant way to the dangerous scenarios it will encounter when it is regularly used by thousands of customers. People have started to think about solutions to this problem—the German government and industry have launched a multimillion-dollar project with that goal—but those efforts have just begun.

The code that will control the vehicle—the brain, so to speak—is not the only thing that must be subjected to scrutiny. The sensors that provide that brain with the data it will use to make decisions must be subjected to equal scrutiny. Engineers must develop new sensor-signal processing and data-fusion algorithms that can discriminate between benign and hazardous objects in a vehicle's path with nearly zero false negatives (hazardous objects

SCIENTIFIC AMERICAN ONLINE To watch a talk by Shladover, go to ScientificAmerican.com/jun2016/cars

3

that were not identified) and extremely low false positives (benign objects that were misclassified, leading to inappropriate responses from vehicles, such as swerving or hard braking).

Engineers cannot resort to the kind of brute-force redundancy used in commercial aircraft systems to achieve these goals because an automated car is a consumer product: it must be affordable for the general public. Turning to artificial intelligence is not an obvious solution, either. Some people have suggested that machine-learning systems could enable automated driving systems to study millions of hours of driving data and then learn throughout the course of their life cycle. But machine learning introduces its own problems because it is nondeterministic. Two identical vehicles can roll off the assembly line, but after a year of encountering different traffic situations, their automation systems will behave very differently.

LEVEL-FOUR FUTURE

I USED TO TELL PEOPLE that level-five fully automated driving systems would not become feasible until after 2040. Somewhere along the way people started quoting me as saying level five would arrive *in* 2040. Now I say that fully automated vehicles capable of driving in every situation will not be here until 2075. Could it happen sooner than that? Certainly. But not by much.

The prospects for level-three automation are clouded, too, because of the very real problem of recapturing the attention, in an emergency, of a driver who has zoned out while watching the scenery go by or, worse, who has fallen asleep. I have heard representatives from some automakers say that this is such a hard problem that they simply will not attempt level three. Outside of traffic-jam assistants that take over in stop-and-go traffic, where speeds are so low that a worst-case collision would be a fender bender, it is conceivable that level-three automation will never happen.

And yet we will see highly automated cars soon, probably within the coming decade. Nearly every big automaker and many information technology companies are devoting serious resources to level-four automation: fully automated driving, restricted to specific environments, that does not rely on a fallible human for backup. When you limit the situations in which automated vehicle systems must operate, you greatly increase their feasibility. (Automated people movers have been operating in big airports for years—but they are on totally segregated tracks.)

In all probability, the next 10 years will bring automated valet-parking systems that will allow drivers to drop their cars at the entrance of a suitably equipped garage that excludes pedestrians and nonautomated vehicles. An onboard automation system will communicate with sensors placed throughout the garage to find out which parking spots are available and navigate to them. Because there will be no need to open the doors, parking spaces can be narrower than they are today, so more cars will be able to fit in garages in areas where space is expensive.

In urban pedestrian zones, business parks, university campuses and other places where high-speed vehicles can be excluded, low-speed passenger shuttles will operate without drivers. In such environments, limited-capability sensors should be adequate to detect pedestrians and bicyclists, and if a sensor detects a false positive and brakes unnecessarily, it will not harm anyone (although it will annoy the people in the vehicle). The CityMobil2 project of the European Commission has been demonstrating such technologies for several years, and its final demonstration is scheduled for this summer.

Segregated bus ways and truck-only lanes will soon enable commercial vehicles to operate at higher levels of automation. Physically segregating these vehicles from other users will greatly simplify threat detection and response systems. Eventually driverless trucks and buses will be able to follow a human-driven lead vehicle in fuel-saving platoons. Researchers worldwide, including the California Partners for Advanced Transportation Technology (PATH) program at the University of California, Berkeley, Japan's Energy ITS project, and the KONVOI and SARTRE projects in Europe, have already tested prototype bus- and truck-platoon systems.

Yet the most widespread implementation of level-four automation within the next decade will probably be automated freeway systems for personal passenger vehicles. These systems will permit automobiles to drive themselves under certain conditions on designated sections of freeway. The vehicles will have redundant components and subsystems so that if something goes wrong, they can "limp home" without human guidance. They will probably be restricted to fair weather on stretches of freeway that have been mapped in detail, down to the signage and lane markings. These sections of road might even have "safe harbor" locations where vehicles can go when they have problems. Most major vehicle manufacturers are hard at work developing these systems, and next year Volvo Cars plans to conduct a public field test of such capabilities with 100 prototype vehicles in Gothenburg, Sweden.

These scenarios might not sound as futuristic as having your own personal electronic chauffeur, but they have the benefit of being possible—even inevitable—and soon. SA

MORE TO EXPLORE

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scientificamerican.com/magazine/sa

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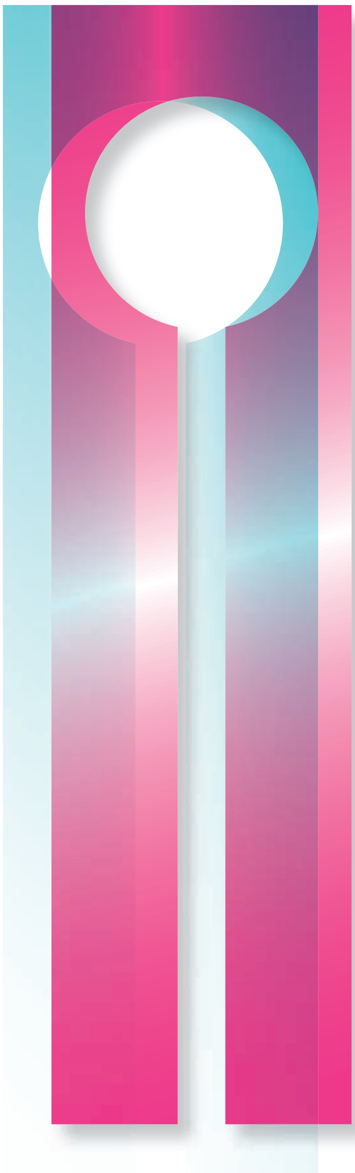

COMMENTARY

SHOULD WE FEAR SUPERSMART ROBOTS?

If we're not careful, we could find ourselves at odds with determined, intelligent machines whose objectives conflict with our own

By Stuart Russell

IT IS HARD TO ESCAPE THE NAGGING SUSPICION THAT CREATING MACHINES smarter than ourselves *might* be a problem. After all, if gorillas had accidentally created humans way back when, the now endangered primates probably would be wishing they had not done so. But *why,* specifically, is advanced artificial intelligence a problem?

Hollywood's theory that spontaneously evil machine consciousness will drive armies of killer robots is just silly. The real problem relates to the possibility that AI may become incredibly good at achieving something other than what we really want. In 1960 legendary mathematician Norbert Wiener, who founded the field of cybernetics, put it this way: "If we use, to achieve our purposes, a mechanical agency with whose operation we cannot efficiently interfere…, we had better be quite sure that the purpose put into the machine is the purpose which we really desire."

A machine with a specific purpose has another property, one that we usually associate with living things: a wish to preserve its own existence. For the machine, this trait is not innate, nor is it something introduced by humans; it is a logical consequence of the simple fact that the machine cannot achieve its original purpose if it is dead. So if we send out a robot with the sole directive of fetching coffee, it will have a strong incentive to ensure success by disabling its own off switch or even exterminating anyone who might interfere with its mission. If we are not careful, then, we could face a kind of global chess match against very determined, superintelligent machines whose objectives conflict with our own, with the real world as the chessboard.

The prospect of entering into and losing such a match should concentrate the minds of computer scientists. Some researchers argue that we can seal the machines inside a kind of firewall, using them to answer difficult questions but never allowing them to affect the real world. (Of course, this means giving up on superintelligent robots!) Unfortunately, that plan seems unlikely to work: we have yet to invent a firewall that is secure against ordinary humans, let alone superintelligent machines.

Can we instead tackle Wiener's warning head-on? Can we de-

maximize human values, but it also does not know exactly what those are. Now the robot actually *benefits* from being switched off because it understands that the human will press the off switch to prevent the robot from doing something counter to human values. Thus, the robot has a positive incentive to keep the off switch intact—and this incentive derives directly from its uncertainty about human values.

The third principle borrows from a subdiscipline of AI called inverse reinforcement learning (IRL), which is specifically concerned with learning the values of some entity—whether a human, canine or cockroach—by observing its behavior. By watching a typical human's morning routine, the robot learns about the value of coffee to humans. The field is in its infancy, but already some practical algorithms exist that demonstrate its potential in designing smart machines.

As IRL evolves, it must find ways to cope with the fact that humans are irrational, inconsistent and weak-willed and have limited computational powers, so their actions do not always reflect their values. Also, humans exhibit diverse sets of values, which means that robots must be sensitive to potential conflicts and trade-offs among people. And some humans are just plain evil and should be neither helped nor emulated.

Despite these difficulties, I believe it will be possible for machines to learn enough about human values that they will not pose a threat to our species. Besides directly observing human behavior, machines will be aided by having access to vast amounts of written and filmed information about people doing things (and others reacting). Designing algorithms that can understand this information is much easier than designing superintelligent machines. Also, there are strong economic incentives for robots—and their makers—to understand and acknowledge human values: if one poorly designed domestic robot cooks the cat for dinner, not realizing that its sentimental value outweighs its nutritional value, the domestic robot industry will be out of business.

Solving the safety problem well enough to move forward in AI seems to be feasible but not easy. There are probably decades in which to plan for the arrival of superintelligent machines. But the problem should not be dismissed out of hand, as it has been by some AI researchers. Some argue that humans and machines can coexist as long as they work in teams—yet that is not feasible unless machines share the goals of humans. Others say we can just "switch them off" as if superintelligent machines are too stupid to think of that possibility. Still others think that superintelligent AI will never happen. On September 11, 1933, renowned physicist Ernest Rutherford stated, with utter confidence, "Anyone who expects a source of power in the transformation of these atoms is talking moonshine." On September 12, 1933, physicist Leo Szilard invented the neutron-induced nuclear chain reaction. SA

sign AI systems whose goals do not conflict with ours so that we are sure to be happy with the way they behave? This is far from easy—after all, stories with a genie and three wishes often end with a third wish to undo the first two—but I believe it is possible if we follow three core principles in designing intelligent systems:

The machine's purpose must be to maximize the realization of human values. In particular, the machine has no purpose of its own and no innate desire to protect itself.

The machine must be initially uncertain about what those human values are. This turns out to be crucial, and in a way it sidesteps Wiener's problem. The machine may learn more about human values as it goes along, of course, but it may never achieve complete certainty.

The machine must be able to learn about human values by observing the choices that we humans make.

The first two principles may seem counterintuitive, but together they avoid the problem of a robot having a strong incentive to disable its own off switch. The robot is sure it wants to

GLOBAL WARMING

PREVENTING TOMORROW'S CLIMATE WARS

The U.S. military is taking steps to limit the chance that worsening droughts, rising seas and melting Arctic ice will hasten uprisings that threaten national interests

By Andrew Holland

IN BRIEF

Climate change is accelerating instability in certain regions and multiplying threats in others. The American military is taking action to prevent consequences that could endanger U.S. interests.

In Africa, the military is trying to lessen conflicts arising from extended drought and loss of farmland. In the Asia-Pacific region, it is helping small nations recover from severe storms so they can remain strong to resist Chinese assertiveness. In the Arctic, it is promoting international laws that would limit Russia from claiming resources and shipping routes.

It is unclear whether the military will commit enough money to sustain such operations. And a Republican president might end support, dismissing climate change as not real.

Photograph by The Voorhes

Andrew Holland is director of studies and senior fellow for energy and climate at the American Security Project, a nonpartisan national security think tank. He has worked on the security threats of climate change since 2007 and has testified before Congress about the U.S.'s future in the Arctic.

DEMOCRATS AND REPUBLICANS MAY OFTEN BE AT ODDS OVER CLIMATE CHANGE, but the U.S. military is not waiting for the debate to be settled. It is preparing for a hotter world, which is already altering geopolitical relations and could lead to armed conflict.

The U.S. Department of Defense breaks the menace into two parts: a direct threat to its infrastructure (think naval bases that face rising seas) and the indirect threats posed around the world if societies become destabilized. The first danger is relatively easy to prepare for: figure out what is vulnerable, then strengthen the infrastructure or move away from the danger.

The second threat is altogether more complicated. Weather, governments and societies are complex systems, so predicting how each will react to higher temperatures is difficult. Yet credible voices have found clear links; a 2015 study published in the *Proceedings of the National Academy of Sciences USA,* for example, noted that climate change fueled the beginning of Syria's civil war by making a regional drought deeper and longer. That drought, when combined with the government's refusal to deal with crop failures and livestock deaths, pushed hundreds of thousands of people to migrate from their farms into cities such as Aleppo and Raqqa. Once protests began in the country in early 2011, many people with little to lose and resentment toward the government joined in. The unrest turned to civil war when the Syrian government started shooting protesters, and that civil war allowed ISIS, also known as the Islamic State of Iraq and Syria, to rise, terrorizing the world.

The U.S. military does not explicitly say that climate change will directly cause wars, but it does call it an "accelerant of instability" or a "threat multiplier." Such language appears in the DOD's formal 2014 Quadrennial Defense Review, its major planning document for the next four years. It also kicks off the department's 2014 Climate Change Adaptation Roadmap, a strategic analysis of how to begin to tackle climate threats.

This past January the department issued a directive telling senior leaders they must now assess and plan for the risks posed by climate change. One new expectation is that humanitarian assistance and disaster response, limited to occasional missions in the past, will become part of almost every deployment because the number of natural disasters worldwide is increasing significantly.

The military has not suddenly become an arm of the Peace Corps. Its mission is to safeguard U.S. interests around the world. Protecting human lives can prevent struggling countries from becoming failed states. Recent history has shown that failed states, such as Afghanistan and Syria, present real threats to U.S. national security by destabilizing regions and breeding terrorists who could threaten Americans.

Concern over climate change feeding violence extends beyond the Defense Department. In October 2015 three former defense secretaries, two former secretaries of state, and 40 senators, military commanders and national security experts—Republican and Democrat—published a full-page open letter as an ad in the *Wall Street Journal* saying that climate change is "shaping a world that is more unstable, resource-constrained, violent, and disaster-prone."

The U.S. military is focusing on two hotspots where climate change could lead to new conflicts—sub-Saharan Africa and the Asia-Pacific region. And it is carefully watching a third, the Arctic. A fourth theater, the Middle East, could also be on the list, but the U.S. Central Command is currently preoccupied with ongoing conflicts there in Syria, Iraq, Yemen and Afghanistan.

AFRICA: DROUGHT AND TERRORISM

GEOGRAPHERS OFTEN JUDGE Africa as the continent most vulnerable to unrest in response to climate change because poverty is widespread, much of the population relies on rain-fed subsistence agriculture, climate variations can be extreme and governance in numerous nations is poor. Disease outbreaks, crop failures, persistent ethnic and religious rivalries, and corruption abound. The continent's population is expected to grow rapidly from 1.2 billion today to double that, or more, by 2050. Adding the stresses of climate change to this already dangerous brew, it is thought, could accelerate the existing threats and tip fragile states toward war.

In fact, it already has. In northern Nigeria deforestation, overgrazing and increased heat from global warming have turned what was once productive farmland and savanna into an extension of the Sahara Desert. Lake Chad has lost more than 90 percent of its original size from drought, mismanagement and waste. Together these factors, along with a Nigerian government that was perceived as unresponsive, led the local population into poverty and prompted migrations to find sustenance and safety.

THREATS: Drought weakened Nigeria, bolstering terrorist group Boko Haram, which kidnapped 276 schoolgirls (*1*). Destructive storms, such as Super Typhoon Haiyan in the Philippines (*2*), can compromise a Pacific nation's ability to stand up to Chinese assertiveness. Dwindling Arctic sea ice allows Russian ships to control more territory (*3*).

DAN KITWOOD *Getty Images* (*protester*); EDGAR SU *Reuters* (*typhoon destruction*); HANNES RADA *Getty Images* (*icebreaker*)

The violent Islamist insurgent group Boko Haram stepped into the miserable vacuum left by these factors. Though originally focused on northern Nigeria, in March 2015 the group pledged allegiance to ISIS, demonstrating a clear threat to U.S. allies and interests. A chain of causation from climate change to desertification, to food insecurity, to migration and then to conflict fueled Boko Haram's rise.

The main mission of the U.S. military's Africa Command (AFRICOM) is to contain existing threats such as Boko Haram and to prevent new ones from starting. (AFRICOM is one of six combat commands based on geography that the U.S. military has formed to cover the globe. Although the Joint Chiefs of Staff and the secretary of defense give direction, each command plans most of its operations.)

Scientists know that warming in Africa will lead to more extreme weather and less water availability, which will lead to lower food productivity in places that already struggle with food security. Warmer temperatures are also allowing mosquitos to expand their range, increasing disease transmission. Those trends, in turn, could cause more poverty and migration, which could lead to local conflicts over increasingly scarce resources, thereby undermining the stability of states and leading to violent uprisings that could rear terrorists. The military's intent is to cut this chain of causation early enough to prevent a war from starting.

One primary strategy is to help build accountable governments and government institutions, nationally and locally. To do that, the military has to know which countries are most vulnerable to climate-related conflicts and then devote resources to strengthening them.

To that end, the DOD funded a 2014 study by the University of Texas at Austin's Climate Change and African Political Stability program. It identified the most vulnerable regions of the continent. Researchers produced granular maps that overlaid climate and other security threats, showing "hot zones" where conflict would be most likely.

One particular zone was the small Central African state of Burundi. Sure enough, in early 2015 a conflict began there when President Pierre Nkurunziza sought a third term in office, even though the constitution limited him to two. Protests and an attempted coup d'état killed roughly 500 people and displaced at least 250,000 more. A cocktail of factors—including climate change—made conflict in an already unstable country more likely. But a full-scale civil war did not erupt, because the Burundian military stayed neutral throughout the crisis. And that neutrality was a testament to the American military, which trained, equipped and reformed the Burundian armed forces over the course of a decade.

Because the U.S. military does not have many boots on the ground or fleets of ships around Africa, AFRICOM's leaders see their role as a hybrid "civil-military" command that works with other parts of the U.S. government, such as the U.S. Agency for International Development, to prop up military and government institutions in African countries. It is ironic that one of the best ways to prevent climate change from sparking conflict has nothing to do with environmental measures.

THE PACIFIC: STORMY SEAS

THERE IS NO SHORTAGE of American military power in the Pacific, and the country is shifting even more of its overall might into this region. The DOD will focus 60 percent of U.S. Air Force and Navy troops on the Pacific by 2020, up from about 50 percent in 2012.

The U.S. Pacific Command (PACOM) has more than enough traditional military threats to care about, including nuclear blackmail in North Korea, boundary disputes in the South and East China Seas, tensions over the political status of Taiwan

and the rising military power of China. Climate change adds two main, overlapping threats to people in the Pacific: more frequent and intense storms caused by warmer oceans, accompanied by rising sea levels. Together these developments could threaten the existence of small island states such as the Marshall Islands, Tuvalu or Micronesia. Sea-level rise could inundate key food-growing regions such as the Mekong River Delta, and storm surges are threatening the long-term viability of major population centers such as Shanghai, Jakarta, Manila and Bangkok. In 2014, a year that did not break any records for frequency or intensity of storms (as 2013 and 2015 did), natural disasters affected 80 million people and caused almost $60 billion in damage, according to the United Nations.

The military's overall aim is to maintain peace, freedom of trade and international law. Meeting those goals in this economically growing region is challenging. Of special concern to U.S. military leaders is China's rapidly expanding naval strength and assertiveness there, which, if uncontested, could allow China to control the area's seas. More than half of the world's trade by ship passes through the South China Sea alone, where China is building military bases on islands it has annexed and physically expanded. The Philippines and other nations claim territory or rights to some of these islands, but Chinese leaders say the land belongs to them.

Climate change factors into the U.S. strategy to build alliances in the region. In cases of natural disasters such as typhoons, which are getting stronger because of climate change, the U.S. Navy is often the only force with the logistical experience to arrive quickly, with enough people and materials, to make a difference immediately after any destruction. China's navy does not have the capability, and the country rarely provides aid to Pacific nations following calamities. The U.S. has solidified alliances with countries around the Pacific by intervening at their hour of maximum need.

A dramatic example occurred in November 2013. Super Typhoon Haiyan hit the Philippines with winds of 195 miles per hour. The storm drove water inland at 46 feet above sea level in some places. More than 7,000 people died, making Haiyan the deadliest typhoon in Philippine history. Immediately after the storm people became desperate for aid. Credible reports came in that the New People's Army, an armed wing of the Communist Party of the Philippines, was attacking government convoys of relief supplies going to remote areas. In the city of Tacloban, eight people were killed, and more than 100,000 sacks of rice were looted from a government warehouse. Society was unraveling.

In response, then Secretary of Defense Chuck Hagel ordered the USS *George Washington*'s battle group, which was on a port visit to Hong Kong, "to make best speed" to the Philippines. Once the aircraft carrier arrived, 13,000 soldiers, sailors, airmen and marines provided food, freshwater and supplies. Their presence stopped the street violence, severing the chain between climate change and conflict.

Less than six months later President Barack Obama visited Manila to sign a new Enhanced Defense Cooperation Agreement that would deepen the alliance between the U.S. and the Philippines. Certainly a big motivation for signing this treaty was to counter China's assertiveness in claiming and occupying islands in the South China Sea. But the quick U.S. response to Haiyan reminded the Philippine government and people, who historically had been skeptical of American military engagement, why it was important to have the U.S. Navy on their side.

Cementing alliances is crucial to U.S. efforts to counter China in Asia. Admiral Samuel Locklear, the recently retired commander of PACOM, said in 2013 that climate change could "cripple the security environment" in the Pacific by destabilizing the region. If an American ally always fears the next typhoon, it is unlikely to invest in the naval forces necessary to deal with traditional security threats, such as the territorial expansion of a rising power.

PACOM activities now include annual events such as the high-level Pacific Environmental Security Forum, coordinating military and civilian communications networks and helping to connect and train military personal, civilian aid workers, local governments and the U.N. The American armed forces are also helping to train Pacific militaries to fight and defeat an enemy, in part through exercises with names such as RIMPAC, Cobra Gold and Balikitan. The teams practice amphibious assaults, major naval actions and combined air defense. These multilateral exercises now also include a simulated humanitarian-assistance mission.

Extreme weather can worsen poverty, leading to uprisings that can destabilize nations, allowing terrorists to expand. The U.S. intends to cut this chain of causation.

THE ARCTIC: OPEN TO AGGRESSION

U.S. ENGAGEMENT in the Arctic is different. The Arctic is warming faster than anywhere else on earth. In less than a decade the territory has undergone a fundamental change in state, from an ocean world enclosed in ice to one open to human exploitation. Sea ice has diminished so extensively that both the Northern Sea Route over Russia and the Northwest Passage over Canada are now open to travel and energy exploration for many months out of the year. Indeed, the rapid melting of Arctic sea ice in 2007 was one of the catalysts prompting the military to think about climate security implications because the U.S. Navy would have a new ocean to patrol. Ironically, though, the military's preparation for the security consequences of climate change in this part of the world seems surprisingly weak.

The Arctic falls under the U.S. Northern Command (NORTHCOM), but the European Command (EUCOM) also plays a role because it is responsible for any military action involving Russia, which is the preeminent military power in the Arctic. In

SCIENTIFIC AMERICAN ONLINE For more on how climate change helped to spark Syria's civil war, see ScientificAmerican.com/jun2016/holland

many ways, the commands face a traditional suite of security challenges: rivalries among great powers, overlapping claims to resources and disputes over freedom of navigation.

A global rush is on to secure the oil and gas that the U.S. Geological Survey says sit underneath the ocean. Shipping companies are hurrying to build Arctic-capable ships that can transit over the top of the world. And countries as far from the Arctic as Singapore and India are pushing to join the Arctic Council, an intergovernmental organization of the eight countries that border or hold Arctic territory, to ensure their interests are represented.

Seeing the scramble begin, in November 2013 the DOD outlined an Arctic strategy. It focuses on defusing potential tensions by promoting diplomacy and boosting the power of transnational institutions.

On paper, the international rule of law in the Arctic is strong; claims to territory in the Arctic Sea are governed by the U.N. Convention on the Law of the Sea (although the U.S. Senate has never ratified it). The Arctic Council is widening its influence by bringing in new observer states (which cannot vote or propose policies) such as China, Italy, Japan and India.

The power of institutions can only go so far, however. In the Arctic, the U.S. Navy faces a competitor with more resources and ambition: the Russian Northern Fleet. Headquartered in Severomorsk off the Barents Sea, the fleet is the country's largest naval operation and conducts regular exercises. It controls the biggest icebreaker fleet on the globe and currently is constructing what will be the world's foremost nuclear-powered icebreaker.

In what are apparently direct orders from President Vladimir Putin, Russia's military has created a Joint Strategic Command North dedicated to protecting the nation's interests in the Arctic Circle. The command has reopened cold war bases across Russia's Arctic coastline, including one at Wrangel Island, only 300 miles from Alaska. Long-range bombers that could test American and Canadian air defenses in the Arctic are being upgraded. And it is worth noting that Putin has displayed a notable disregard for borders and international rules in recent dealings in Ukraine. Few people would have predicted even a short time ago that Russia would invade and annex the Crimea.

China has also shown a growing interest in the Arctic, sending its Snow Dragon icebreaker through the Northwest Passage on a highly publicized 2012 tour to Iceland.

Despite such stresses, the American military says it sees no need for a surface naval presence north of the Bering Strait, maintaining that it can meet its mission with submarine patrols alone. This strategy is being tested as both Russia and China make very public maneuvers in the Arctic, however. To counter them, the U.S. could also show a greater "presence" with port visits to Iceland and exercises with NATO allies. History has shown time and again that when a powerful nation expands to claim more land, more sea or more natural resources, if other powers do not push back the expansion continues until a border war erupts.

Even so, NORTHCOM is reluctant to expand its Arctic presence, in part because of money. It has said that operations in the Arctic would be extremely costly. As it stands, the U.S. Navy does not have the infrastructure, the ships or the political ambition to sustain surface operations there. The coast guard has only two icebreakers, and one of them, the Polar Star, is 40 years old. (Icebreakers are needed, even as sea ice retreats, because they provide year-round access and because ice flows are unpredictable and could trap ordinary ships.) In a September 2015 visit to Alaska, President Obama announced plans to build a new icebreaker by 2020, but it could cost more than $800 million. In a strained federal budget environment, where even the military has to fight for funds, no admiral is looking to add a pricey new mission.

In light of the disparity, perhaps the U.S. military sees diplomacy and cooperation as a cost-effective way to ensure that American interests are heard. Such a low-key approach, however, is drawing fire from opponents in Congress. Senator Dan Sullivan of Alaska, a Republican who sits on the Senate Committee on Armed Services, has repeatedly pressed the Obama administration to devote more military resources to the Arctic. He recently convinced Secretary of Defense Ashton Carter to pledge to develop an operations plan that will determine what forces would be necessary to successfully defend American interests in the event of conflict there.

As of now, however, the U.S. military is doing little to expand its presence north of the Arctic Circle, even as its competitors invest heavily in the region.

WILL THE NEXT PRESIDENT CARE?

IT HAS TAKEN A LONG TIME for foreign policy and national security experts to persuade the U.S. military to prepare for a changing climate. The looming question is whether the early efforts will continue when a new president takes office in January 2017. The issue of climate change remains frustratingly political, with many Republicans dismissing it altogether.

Another pressing question is whether the military will devote enough money to climate-related efforts. The Arctic approach is not encouraging. The main source of funding for civilian-assistance operations by the DOD is the Overseas Humanitarian, Disaster and Civic Aid program, but its annual appropriation has declined to about $100 million even though the mission has been expanding.

Ultimately the truth always wins: the climate is changing, and the military commands will have to deal with its effects. It is certainly better to plan in advance for possible threats than to respond after the fact. Right now the military will not suffer a sneak attack from climate change—two of the six commands, at least, are starting to face the threat head-on. Whether that is enough to continue to cut the chain from climate change to conflict is uncertain. SA

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Some fish species turn out to be surprisingly good problem solvers. At times, they even use tools

By Jonathan Balcombe

ZOOLOGY

EINSTEIN OF THE SEA

WHILE DIVING OFF THE MICRONESIAN ARCHIPELAGO OF PULAU, EVOLUTIONARY biologist Giacomo Bernardi witnessed something unusual and was lucky enough to capture it on film. An orange-dotted tuskfish (*Choerodon anchorago*) uncovered a clam buried in the sand by blowing water at it, picked up the mollusk in its mouth and carried it to a large rock 30 yards away. Then, using several rapid head flicks and well-timed releases, the fish eventually cracked open the clam against the rock. In the ensuing 20 minutes, the tuskfish ate three clams, using the same sequence of behaviors to smash them.

Bernardi, a professor at the University of California, Santa Cruz, is thought to be the first scientist to film a fish demonstrating tool use. By any measure, it is remarkable behavior from a fish. Tool use was long believed unique to humans, and it is only in the past decade that scientists have begun to appreciate the behavior beyond mammals and birds.

Bernardi's video unveils new gems every time I watch it. Initially I failed to notice that the enterprising tuskfish does not uncover the clam in a manner we might expect—by blowing jets of water from its mouth. The fish actually turns away from the target and snaps its gill cover shut, generating a pulse of water the same way that a book creates a puff of air when you close it. And it is more than tool use. By using a logical series of flexible behaviors separated in time and space, the tuskfish is a planner. This behavior brings to mind chimpanzees' use of twigs or grass stems to draw termites from their nests. Or Brazilian capuchin monkeys that use heavy stones to smash hard nuts against flat boulders that serve as anvils. Or crows that drop nuts onto busy traffic intersections and then

WARREN PHOTOGRAPHIC

ARCHERFISH squirts precisely tuned jets of water to knock down unsuspecting prey.

swoop down during a red light to retrieve the fragments that the car wheels have cracked open for them.

Halfway to its destination, our tuskfish stops to try out a smaller rock lying on the sand. It makes a couple of halfhearted whacks, then heads on its way again, as if it has decided this one is not worth his time. (Who can't relate to these misguided attempts and how they reflect the fallibility of a mortal life?)

These are impressive cognitive feats for any animal. That they are performed by a fish clearly upsets the still commonly held assumption that fishes are at the dim end of the animal intelligence spectrum. As does the realization that what Bernardi saw that day was not exceptional. Scientists have noticed similar behavior in green wrasses, also called blackspot tuskfish (*Choerodon schoenleinii*), on Australia's Great Barrier Reef; in yellowhead wrasses (*Halichoeres garnoti*) off the coast of Florida; and in a sixbar wrasse (*Thalassoma hardwicke*) in an aquarium setting. In the case of the sixbar wrasse, the captive fish was given pellets that were too large to swallow and too hard to break into pieces using only its jaws. The fish carried one of the pellets to a rock in the aquarium tank and smashed it much as the tuskfish did the clam. The zoologist who observed this, Łukasz Paśko of the University of Wrocław in Poland, saw the wrasse perform the pellet-smashing behavior on 15 occasions, and it was only following many weeks of captivity that he had first noticed it. Paśko described the behavior as "remarkably consistent" and "nearly always successful."

Hard-nosed skeptics might point out that this kind of thing is not *real* tool use because the fishes are not wielding one object to manipulate another, as humans do with an ax splitting a log for firewood or a chimpanzee does by using a stick to get to the tastiest termites. Paśko himself refers to the wrasse's actions as "tool-like." But this is not to demean the behavior, because, as he points out, smashing a clam or a pellet with a separate tool is simply not an option for a fish. For one thing, a fish is not equipped with grasping limbs. In addition, the viscosity and density of water make it difficult to generate sufficient momentum with an isolated tool (try smashing a walnut shell underwater by throwing it against a rock). And clasping a tool by mouth, the fish's other practical option, is inefficient because fragments of food would float away, only to be snatched up by other hungry swimmers.

EXPERT AIM

JUST AS THE TUSKFISH uses water as a force for moving sand, the archerfish (*Toxotes*) also uses water as a force—only this time as a hunting projectile. These four-inch-long tropical marksmen—sporting a row of handsome black patches down their silvery sides—mostly inhabit brackish waters of estuaries, mangroves and streams from India to the Philippines, Australia and Polynesia. Their eyes are sufficiently wide, large and mobile to allow binocular vision. They also have an impressive underbite, which they use to create a gun barrel of sorts. By pressing their tongue against a groove in the upper jaw and suddenly compressing the throat and mouth, archerfish can squirt a sharp jet of water up to 10 feet through the air—with an accuracy in some individuals of nearly 100 percent at a distance of three feet. Woe betide a beetle or a grasshopper perched on a leaf above the backwaters where these fish lurk.

The behavior is notably flexible. An archerfish can squirt water in a single shot or in a machine gun–like fusillade. Targets have included insects, spiders, an infant lizard, bits of raw meat, scientific models of typical prey and even observers' eyes—along with their lit cigarettes. Archerfish also load their weapons according to the size of their prey, using more water for larger, heavier targets. Experienced archers may even aim just below their prey on a vertical surface to knock it straight down into the water instead of farther away on land.

Using water as a projectile is only one of many foraging options for the archerfish. Most of the time this species forages underwater as ordinary fishes do. And if a meal is within just a foot of the surface of the water, they may just take the more direct route, leaping to snatch it in their mouth.

Archerfish live in groups, and they have fantastic observational learning skill. Their hunting prowess does not come preinstalled, so novices can make successful shots at speedy targets only after a prolonged training period. Researchers studying captive archerfish at the Friedrich-Alexander University of Erlangen-Nürnberg in Germany found that inexperienced individuals were not able to successfully hit a target even if it was moving as slowly as half an inch per second. But after watching 1,000 attempts (successful and unsuccessful) by another archerfish to hit a moving target, the novices were able to make successful shots at rapidly moving targets. The scientists concluded that archerfish can assume the viewpoint of another archerfish to learn a difficult skill from a distance. Biologists call this "perspective taking." What an archerfish does might not require the same level of cognition as that shown by a captive chimp that has carried a disabled starling up a tree to help launch it back to the air, but it is nonetheless a form of grasping something from the perspective of another.

High-speed video recordings reveal that these fish use different shooting strategies depending on the speed and location of flying prey. When using what the researchers describe as the "predictive leading strategy," archerfish adjust the trajectory of their jets of

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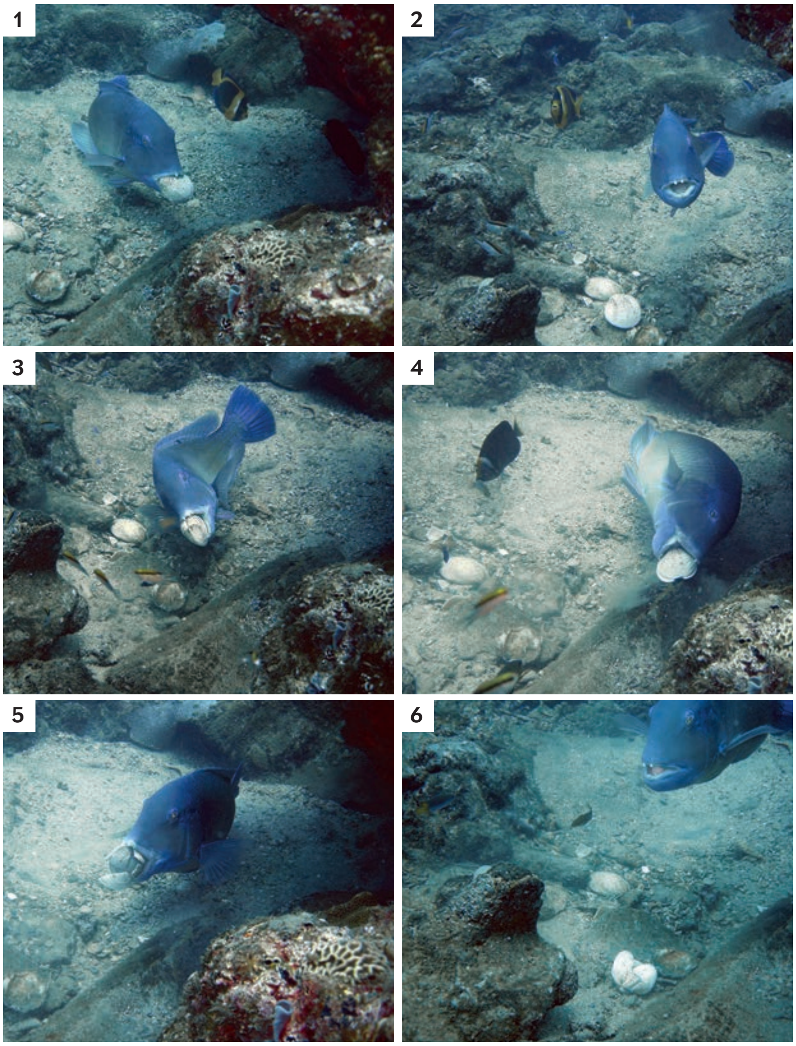
IN BRIEF

Fishes have long been dismissed as dullards, but new observations and studies are proving this assumption wrong.

One species of wrasse, for instance, has been filmed engaging in a marine version of tool use.

Archerfish, which capture prey with precisely calibrated jets of water, are showing how fishes can learn complex skills—and that they can mentally place themselves in the position of a fellow fish.



BLACKSPOT TUSKFISH opens a cockle by smashing it onto a rock, which some scientists suggest is an example of tool use.

COURTESY OF SCOTT GARDNER

water to account for the speed of a flying insect—they aim farther ahead of the target if it is moving faster. If the target is flying low (usually less than seven inches above the water), archerfish often use a different strategy, which the researchers term "turn and shoot." This maneuver involves the fish firing while simultaneously rotating its body horizontally to match the lateral movement of the target, causing the jet of water to "track" the target on its airborne path. These fish would do any quarterback proud.

Archerfish can also compensate for the optical distortion produced by the water-to-air transition by learning the physical laws governing apparent target size and the fish's relative position to the target. Having such a generalizable "rule of fin" enables an archerfish to gauge absolute sizes of objects from unfamiliar angles and distances. I wonder if archerfish also practice entomology, visually identifying insects to know whether they are tasty, whether they are too big to eat or too small to bother with, or whether they sting.

Most likely, archerfish have been squirting water jets for at least as long as humans have been throwing stones, and I suspect that wrasses were using rocks to crack clams open long before our ancestors started bashing hot metal against anvils in the Iron Age. But can fishes spontaneously invent tool use, as we can when unexpected conditions require us to improvise? In May 2014 a study highlighted an example of innovative tool use by Atlantic cods being held in captivity for aquaculture research. Each fish wore a colored tag affixed to its back near the dorsal fin, which allowed the researchers to identify each individual fish. The holding tank had a self-feeder activated by a string with a loop at the end, and the fish soon learned they could release a morsel of food by grabbing the loop in their mouth and pulling on it.

Apparently, some of the cods discovered they could activate the feeder by hooking the loop onto their tag and swimming a short distance away. These clever cods honed their technique through hundreds of "tests"—and it became a finely tuned series of goal-directed, coordinated movements. It also demonstrated true refinement because the innovators were able to grab the pellet a fraction of a second faster than by using their mouth to get the food. That fishes are routinely expected to interact with a foreign device to feed themselves is impressive enough but that some devised a new way of using their tag, in this case, shows a fish's capacity for flexibility and originality.

Tool use by fishes seems confined to a limited number of fish groups. Australian fish biologist Culum Brown suggests wrasses in particular may be fishes' answer to the primates among mammals and the corvids (crows, ravens, magpies and jays) among birds in having a greater than expected number of examples of tool use. It could just be that living underwater offers fewer opportunities for it than living on land. But we do know the tuskfish and the archerfish are prime examples of evolution's boundless capacity for problem solving, and they might turn out to have plenty of company among other fishes. SA

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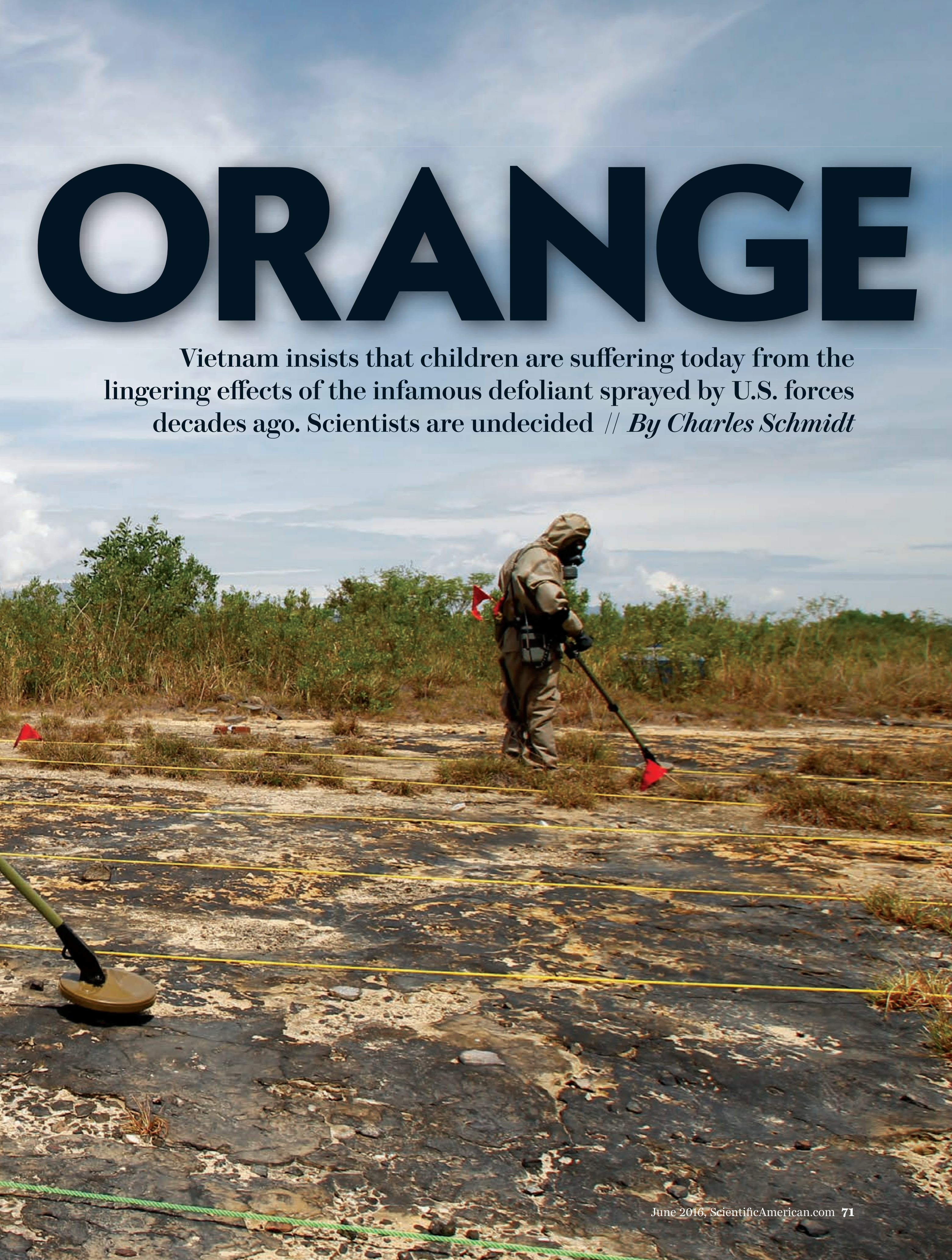
THE FOG OF AGENT

SOLDIERS at Da Nang airport in Vietnam search for unexploded bombs in 2011, before workers excavated the soil there and heated it to destroy dioxin, a toxic compound in Agent Orange. The U.S. military sprayed the defoliant during the Vietnam War in the 1960s.

ORANGE

Vietnam insists that children are suffering today from the lingering effects of the infamous defoliant sprayed by U.S. forces decades ago. Scientists are undecided // *By Charles Schmidt*



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祝大家阅读愉快！

Charles Schmidt is a freelance journalist based in Portland, Me., covering global health and the environment. He visited Vietnam to report on the lasting legacy of Agent Orange.

AFTER HE WAS BORN with a cleft lip and palate and congenital heart disease, Danh (not his real name) spent his first month in an incubator struggling to breathe. He is now eight years old and thin as a rail. Danh has an endearing smile, but he can't speak, and his mother, Lien (also a pseudonym), says he is mentally disabled. Recently he sat playing with toy cars at home in Da Nang, Vietnam, while Lien talked wearily about her son's many needs.

I had been brought to Lien by a private American aid group called Children of Vietnam that works with poor families in Da Nang. We sat drinking tea in a simple room open to the street, chatting over the din of traffic. Family pictures hung next to a portrait of Ho Chi Minh, Vietnam's communist revolutionary leader. Lien's otherwise soft features hardened when I asked what she thought had caused her son's disabilities. "Agent Orange did this!" she exclaimed through an interpreter, her eyes flashing with anger.

Agent Orange was a defoliant sprayed by the U.S. during the Vietnam War to clear dense vegetation and reveal enemy troops. It was contaminated with dioxin, a potent toxicant that persists for decades in the environment. Danh's grandfather fought in the heavily sprayed Central Highlands, and his father worked at the former U.S. air base in Da Nang, where dioxin was later discovered in the ducks and fish eaten frequently by local villagers. Dioxin has been associated with human cancers, heart disease and other health problems in people who are exposed. But Lien firmly believes her son inherited the toxic legacy of her father and grandfather's exposure. The Vietnamese government, which classifies Danh as a suspected "victim of Agent Orange," claims that hundreds of thousands of its citizens born one and even two generations after the war are battling health effects of dioxin passed down by their parents.

The U.S. government gives modest compensation to American war veterans for health problems such as leukemia, Hodgkin's disease and Parkinson's disease that are attributed to Agent Orange, based on detailed military records of soldiers who had "boots on the ground" during the spray operations. Scientists used those records in studies that later associated Agent Orange with more than a dozen ailments in service men and women. But the government has refused to acknowledge claims that the defoliant also harmed the Vietnamese, in part because it says Vietnam has not provided strong data on who was exposed. Medical records in the country are spotty, and the population was also highly mobile in the chaotic postwar years, making exposures to Agent Orange difficult to prove.

Vietnam claims its data are sound, but the disagreement has sustained tension for years, particularly about effects that might be passed down to subsequent generations. Although U.S. laboratory tests in animals show that genetic damage caused by dioxin can be passed on to offspring, susceptibility varies widely by species, and no studies have been done in humans. Whether animal findings reflect the human experience "would be notoriously difficult to prove," cautions Robert Moore, a toxicology researcher at the University of Wisconsin–Madison.

Looking to smooth relations, in December 2014 Congress passed a five-year, $21-million humanitarian aid package that, for the first time, provides assistance specifically for severely disabled people living in areas that were sprayed during the war. Charles Bailey, former director of the Agent Orange in Vietnam Program at the Aspen Institute, describes the aid as a breakthrough that "ensures that our humanitarian assistance goes to those with the greatest need." But the aid package does not explicitly reference

IN BRIEF

Vietnamese doctors claim that the defoliant Agent Orange, sprayed during the Vietnam War, causes genetic defects in children and grandchildren of people who were exposed.

U.S. animal tests show that genetic damage from dioxin in Agent Orange can be passed on to offspring, but species vary widely in how susceptible they are. No human studies exist.

American scientists say Vietnamese research linking Agent Orange exposure to birth defects is flawed. Authorities there have not allowed American experts to conduct studies in Vietnam.

Without admitting guilt, Congress approved $21 million to help disabled people in Vietnam, but that country says the aid should be far higher.

PRECEDING PAGES: NGUYEN HUY KHAM *Reuters;* THIS PAGE: KAZUYOSHI NOMACHI *Corbis*

VIETNAM SAYS hundreds of thousands of children and grandchildren of citizens exposed to Agent Orange suffer from birth defects, such as those shown here, including one individual who has a hand and shoulder but no arm. The U.S. government notes there are many causes of birth defects.

PAULA BRONSTEIN *Getty Images (left)*; CHAU DOAN *Getty Images (right)*

Agent Orange as having caused those disabilities. It is more a symbolic gesture meant to assuage the Vietnamese position than an admission of culpability. Forty years have passed since U.S. forces fled Saigon (now Ho Chi Minh City), marking the end of the war. Yet fundamental questions about the multigenerational health legacy of Agent Orange in Vietnam remain hotly contested.

DIOXIN IS THE VILLAIN

WITH ITS LEAFY BOULEVARDS, resorts and trendy cafes, today's urban Da Nang is a far cry from the port town that hosted U.S. forces during the war. Scooters and motorcycles fill the main road heading toward the old Da Nang airbase, which is now an international airport. It was from there in 1962 that U.S. and South Vietnamese forces launched Operation Ranch Hand, the herbicidal warfare program.

Produced mainly by Monsanto and Dow Chemical, Agent Orange was a 50–50 mixture of two herbicides—2,4-D and 2,4,5-T—that was sprayed by U.S. troops at the initial request of the South Vietnamese government. Troops also sprayed other mixtures during the war, including agents White, Blue, Pink, Green and Purple, each named for the color of a striped band around the drums it was transported in. The primary goal was to strip away the jungle cover hiding enemy forces, and the spraying took place mainly in South Vietnam and parts of Laos. C-123 aircraft sprayed herbicides from the air, and within two days all the plants touched by the chemicals were dead.

It was not until 1969 that Agent Orange and most of the other mixtures were found to be inadvertently contaminated with the most toxic form of dioxin, known as TCDD. By the time Operation Ranch Hand wrapped up in 1971, two years after the contamination was discovered, at least 20 million gallons of herbicides had been sprayed, exposing 2.1 million to 4.8 million villagers, according to a definitive analysis published in 2003 by Jeanne Stellman, now a professor emeritus of health policy and management at Columbia University.

Animal studies show that TCDD is one of the most poisonous chemicals known. Apart from causing liver damage, cancer and immune problems in directly exposed animals, TCDD is exquisitely toxic to developing babies in the womb. Fed to a pregnant rat, a dose of less than one part per billion—comparable to a single drop in 14,000 gallons of water—will induce female sexual characteristics in a male embryo. Doses on the order of 100 parts per billion in rodents and fish will cause birth defects such as cleft palate, malfunctioning kidneys, heart problems and weak bones.

But TCDD works in mysterious ways: some species succumb to minuscule doses, whereas others are more resistant to its effects. Certain species start out sensitive and then become more resistant with age. There are even differences within species, says Linda Birnbaum, director of the National Institute of Environmental Health Sciences in Research Triangle Park, N.C. Human susceptibility is unknown because studies cannot be done ethically. That uncertainty drives pitched scientific debates over what constitutes a potentially "safe" level of human exposure.

DNA DAMAGED FOR GENERATIONS?

AT THE WAR REMNANTS MUSEUM in Ho Chi Minh City, a visitor might get the impression that the science is settled. Images of grotesquely disfigured people hang on orange walls next to maps showing where the defoliants were sprayed. A sign proclaims that dioxin's effects "can be transmitted to many generations through the damage to DNA molecules and genes." Hospitals in Vietnam have entire wards devoted to the care of purported Agent Orange victims, including the grandchildren of individuals said to have been exposed.

Studies with rats do not prove that generations of Vietnamese are experiencing effects from dioxin, but they suggest that such a scenario is at least plausible. In this situation, initial exposure during the war would have reprogrammed embryonic sperm or egg cells (also known as germ cells) at vulnerable peri-

ods during pregnancy, leading to changes being passed from one generation to the next.

Scientists are now making important advances that suggest the chemical has long-lasting and even transgenerational effects. Emerging evidence in rodents at labs around the world shows that TCDD alters the epigenome—the biological system that controls which genes in a cell are turned on or off. It is because of this so-called epigenetic regulation that all the cells in a developing embryo, even though they inherit the same genes from the mother and father, go on to form different tissues. The genes that cause a cell to beat in the heart, for instance, are activated by one epigenetic process, whereas another process turns off genes that would allow that cell to transmit nerve impulses in the brain.

TCDD can reprogram those epigenetic controls, with consequences that might appear long after the chemical has been cleared from the body. "The effects don't necessarily occur at the time of exposure," explains Michael Skinner, a biologist at Washington State University. "Instead the epigenome can be stuck in an altered state, with effects that can occur at anytime during your life." Supporting evidence comes from the lab of Alvaro Puga, a molecular biologist at the University of Cincinnati College of Medicine, who gave pregnant mice TCDD and found that the pups were born with nonlethal heart defects that became dangerous only when the animals reached adulthood.

When Skinner gave pregnant rats high doses of TCDD, he found that the second- and third-generation offspring had elevated rates of ovarian and kidney disease and that the fourth generation had lower sperm counts. Asked if those results were relevant to the experience of humans exposed to dioxin in Vietnam, Skinner emphatically answered, "Yes." Some scientists question that connection as well as the relevance of his studies to Vietnam, in part because he subjected his rats to doses far higher than would occur in the human population.

AGENT ORANGE defoliated trees, revealing troops. One mangrove forest in 1970 (*bottom*) was still devastated five years after being sprayed, in contrast with another that was untouched (*top*).

AP PHOTO

The Vietnam case is complicated by the persistence of TCDD in the environment, which might have ongoing effects independent of those passing through the germ line. TCDD's half-life in the human body ranges from seven to 10 years. Its half-life in soils and sediments can last decades longer, allowing the compound to build up in fish and ducks, both staples of the Vietnamese diet—the very diet of eight-year-old Danh's father.

Studies conducted between the 1990s and mid-2000s by Vancouver-based Hatfield Consultants revealed seven hotspots—areas where soil and sediment measurements exceed 1,000 parts per trillion (new numbers suggest as many as 28 hotspots). According to Thomas Boivin, Hatfield's director of international operations, the top three hotspots were all former South Vietnamese and U.S. air bases in Da Nang, Phu Cat and Bien Hoa. In a 2015 study, scientists at the U.S. Centers for Disease Control and Prevention's Agency for Toxic Substances and Disease Registry found that fish collected from ponds at Bien Hoa were still contaminated at unsafe levels.

Puga thinks TCDD might build up in the fat stores of people who eat contaminated food until it reaches a state in which it accumulates faster than the body can eliminate it. If fat releases the compound into a woman's blood during pregnancy, he says, the "baby could get a whopping dose." Yet without better exposure data and TCDD measurements in blood, that scenario amounts to little more than conjecture. Birth defects already afflict 3 percent of all newborn children worldwide, and the Vietnamese rank among the world's top users of agricultural pesticides, which experiments show can cause birth defects in animals. The population is also chronically deficient in dietary folic acid, a nutrient that protects against nervous system defects during pregnancy.

ELUSIVE DATA

WHILE CITING unpublished Vietnamese studies, Le Ke Son, who recently retired as director of Committee 33, a government group responsible for Agent Orange activities in Vietnam, insisted in an e-mail exchange with me that "rates of birth deformities and childbirth incidents in the sprayed areas and the hotspots are definitely higher than in the control areas." Le Ke Son is a medical doctor and a toxicologist and continues to lead the national research program on dioxin in Vietnam. His views are considered more reasonable than those of government hard-liners.

U.S. scientists typically dismiss the Vietnamese research, however, noting that it rarely appears in high-quality Western journals. Vietnamese authorities have also not allowed American experts to conduct their own studies in Vietnam. Officials stopped Arnold Schecter, now an adjunct professor at the University of Louisville School of Medicine, as he tried to leave the country with human blood samples for dioxin analysis in 1995.

Hope for cooperation on studies rose in 2000, when David Carpenter, director of the Institute for Health and the Environment at the University at Albany, State University of New York, proposed a five-year, $1-million project. He would take blood samples from women who were about to give birth at hospitals in three cities: Ho Chi Minh, which was near the center of prior Agent Orange exposures; Hanoi, which was far away, and the province of Thua Thien Hue, which was also extensively sprayed. Levels of TCDD in

SCIENTIFIC AMERICAN ONLINE For more on how dioxin's effects may be passed to offspring in lab rats, see ScientificAmerican.com/jun2016/schmidt

blood would be correlated with three kinds of birth defects: lack of limbs, neural tube defects, and cleft lip and palate.

But the plan unraveled. According to Carpenter, the National Institutes of Health made approval conditional on Vietnam's okay. Hanoi took a year, after which the NIH declared it would only support a $350,000 pilot study. Vietnam balked. After further roadblocks, the NIH and the university ended the project.

"I wasted three years of my life writing those proposals and making multiple trips to Vietnam, and it all came to nothing," Carpenter says. "That was the best chance for a collaborative study, and I'm sure it's not going to happen again." Carpenter says the proposed work made both Hanoi and Washington nervous. "U.S. officials worried that if we associated birth defects with dioxin, then we'd be liable for reparations," he says. "And the Vietnamese worried that if we didn't make that association, they'd lose the propaganda benefits of blaming us for the birth defects."

Carpenter concedes that pulling off the study, or a new one like it, will be difficult. A sizable blood sample, 40 milliliters, is needed for dioxin analysis. And the testing technology is complex and exists in only a few labs around the world, he says.

New results could provide much needed clarity. A comprehensive review of Vietnamese birth defects data was done 30 years ago. Maureen Hatch, currently a staff scientist at the National Cancer Institute, had reviewed Vietnamese studies, medical records and government statistics and found a litany of problems, including few prewar baseline measures and inadequate controls from unsprayed areas. Still, in a 1985 paper in *Teratogenesis, Carcinogenesis, and Mutagenesis,* she and her co-author, John Constable, wrote that some studies did "seem to show a large number of striking and usually rare anomalies." Some babies were born missing brain and skull parts; others were born without eyes or with shrunken, malformed limbs.

The best association with the TCDD in Agent Orange, she and Constable concluded, was for molar pregnancy. In these cases, sperm fertilizes a nonviable egg, creating a mass of tumorlike tissue that grows in the uterus and occasionally becomes cancerous. A more recent meta-analysis concluded that parental exposure to Agent Orange in Vietnam appears to be associated with an increased risk of birth defects, but the conclusions are limited.

American analysis of U.S. soldiers who were exposed, carried out by the Institute of Medicine since 1991, is more definitive. The institute's 2014 biennial report says there is "sufficient evidence of an association" with soft-tissue sarcoma, non-Hodgkin's and Hodgkin's lymphomas, and chloracne (skin blisters). It also cites "limited or suggestive evidence" for laryngeal, lung and prostate cancers, multiple myeloma, early-onset peripheral neuropathy, Parkinson's, hypertension, ischemic heart disease, stroke and type 2 diabetes. Notably, the report calls evidence for any kind of birth defect "inadequate" except for spina bifida, which falls into the "limited or suggestive" category. The U.S. Department of Veterans Affairs provides compensation for these health effects if vets can prove they were exposed to Agent Orange.

A PAYOFF FREE OF GUILT

THE INSTITUTE OF MEDICINE'S classifications seem to be American admissions of direct effects from Agent Orange. Yet questions over whether the defoliant played a role in health problems in Vietnam, especially in subsequent generations, are "trapped in a Sargasso Sea of disputes over causality, liability, compensation and responsibility," Bailey says. The new aid package, he asserts, skirts those disputes and simply prioritizes federal assistance to smaller groups of people with more profound disabilities.

Senator Patrick Leahy of Vermont, who has long worked to tackle the war's lingering environmental threats, coordinated the aid. During the 1980s Leahy was instrumental in the creation of a federal fund that to this day pays to remove unexploded bombs still littering the Vietnamese countryside. Since 2007 he has secured about $100 million for dioxin cleanup in Vietnam. "I think we're past the point of tying compensation to the science," says Timothy Rieser, a legislative aide who works for Leahy on Agent Orange issues. "The U.S. government has by its actions accepted the likelihood that some people were severely affected. And the question now is, How can we best address that?"

Le Ke Son, formerly of Committee 33, agrees that humanitarian aid should prioritize disabled people in the hotspots, including Da Nang, Bien Hoa and other sprayed areas. "I think $21 million is a good step for the U.S. government," he says. "But it isn't enough."

In an e-mail exchange with me, a spokesperson for Monsanto neither confirmed nor denied any contamination or possible health effects from exposure to the defoliant. It noted that the Monsanto that manufactured Agent Orange was a former company and that the current company only shares the same name. Furthermore, the spokesperson added, "U.S. courts have determined that the contractors who manufactured Agent Orange for the government are not responsible for claims associated with the military use of Agent Orange because the manufacturers were government contractors carrying out the instructions of government." The spokesperson declined to comment on whether dioxin could have transgenerational effects. Dow Chemical, in an e-mail, said it would not address my questions; a statement on the company's Web site asserts that the U.S. government "specified how Agent Orange would be produced and then subsequently controlled its transportation, storage and use."

In Stellman's view, "chemical companies and a large segment of the U.S. government" would prefer that health problems in Vietnam never be linked conclusively to Agent Orange. On the other hand, she says, "the Vietnamese see just about every birth defect in their country as being caused by Agent Orange exposure. Both sides, however, are off base. Some birth defects in Vietnam are likely attributable to Agent Orange, but the degree to which that's true now is not a question that science can answer. There still hasn't been a definitive study." SA

MORE TO EXPLORE

Agent Orange and Risks to Reproduction: The Limits of Epidemiology. Maureen C. Hatch and Zena A. Stein in *Teratogenesis, Carcinogenesis, and Mutagenesis,* Vol. 6, No. 3, pages 185–202; 1986.

Dioxin (TCDD) Induces Epigenetic Transgenerational Inheritance of Adult Onset Disease and Sperm Epimutations. Mohan Manikkam et al. in *PLOS ONE,* Vol. 7, No. 9, Article No. e46249; September 26, 2012. **http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0046249**

Veterans and Agent Orange: Update 2012. Institute of Medicine. National Academies Press, 2014.

Children of Vietnam, a nonprofit aid group: **www.childrenofvietnam.org**

FROM OUR ARCHIVES

"A Great Poison." Marguerite Holloway; November 1990.

scientificamerican.com/magazine/sa

RECOMMENDED

By Clara Moskowitz

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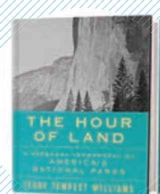
MILKY WAY glows over Grand Teton National Park in Wyoming.

BABAK TAFRESHI *Getty Images*

The Hour of Land: A Personal Topography of America's National Parks

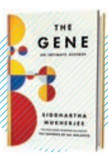
by Terry Tempest Williams. Sarah Crichton Books, 2016 ($27)



The National Park Service was established a century ago this August to protect the U.S.'s natural treasures, historic sites and national monuments. In this essay collection, writer and conservationist Williams chooses 12 of the 410 places that fall under the National Park Service's protection, reflecting on both the history and power of these locales and their personal meaning to her. For instance, Williams grew up exploring Grand Teton National Park with her family and worked at the Teton Science Schools. The parks she features span the nation, from Alcatraz Island in California to Acadia National Park in Maine. They recall both highlights and low points in America's history—from the triumph of the National Park Service as a way to protect wild spaces to the harsher realities of bloodshed at Gettysburg National Military Park and the displacement of native peoples in the name of preservation. *—Jennifer Hackett*

The Gene: An Intimate History

by Siddhartha Mukherjee. Scribner, 2016 ($32)



Writer Mukherjee's interest in genetics is both professional and personal. He is a doctor and a professor of medicine, and mental illness runs in his family. Through the poignant stories of an uncle and a cousin with schizophrenia, as well as an uncle with bipolar disorder, Mukherjee shows the devastating life consequences for those afflicted and examines the shadow that knowledge of an inherited risk can cast on an entire family.

This background impelled him to write this history of genetics, which spans from Gregor Mendel's 19th-century experiments pointing the way toward the idea of the gene to today, when scientists can easily sequence entire genomes and are experimenting with editing human genes. Mukherjee inspires both awe at how thoroughly genetics allows us to understand our own bodies and selves and wariness at the moral risks inherent in the literally life-changing abilities the field has introduced.

Rise of the Machines: A Cybernetic History

by Thomas Rid. W. W. Norton, 2016 ($27.95)

In this book, Rid, a professor of security studies, traces how computers became so ubiquitous and integral to our lives. During World War II, advances such as radar and antiaircraft weapons demonstrated the vast potential of mechanized technology, prompting governments around the world to invest seriously in computing.

In the decades that followed, groups as divergent as the military, hippies and anarchists learned to use new technologies to further their own causes. We have now come to a point, Rid writes, of unprecedented enthrallment with computers at the same time as we are being forced to grapple with the dilemmas they have introduced, such as the increasingly dangerous threat of hacking. In an age when governments and start-ups alike worry deeply about cybersecurity, Rid's account of how the relationship between human and machine developed is quite timely. *—J.H.*

The Life Project: The Extraordinary Story of 70,000 Ordinary Lives

by Helen Pearson. Soft Skull Press, 2016 ($17.95)

Why does a person's life take a particular course? This existential question is also a scientific one because researchers now know that many demographic factors—such as education, sex, race and, especially, economic circumstances—have a profound influence on how our lives turn out.

Scientists study these effects through birth-cohort studies, which periodically record information about the health and welfare of children born around the same time. Of these, the British birth-cohort studies, begun in 1946 and repeated with additional cohorts in 1958, 1970 and 2000, are the longest-running and most comprehensive. Pearson, an editor at *Nature,* follows the history and revelations of these projects and probes the power of our surroundings to influence human development, as well as the potential for individuals to rise beyond their circumstances.

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His book *The Moral Arc* (Henry Holt, 2015) is now out in paperback. Follow him on Twitter @michaelshermer

Death Wish

What would be your final words?

By Michael Shermer

Between December 7, 1982, and February 16, 2016, the state of Texas executed 534 inmates, 417 of whom issued a last statement. This January in the journal *Frontiers in Psychology,* psychologists Sarah Hirschmüller and Boris Egloff, both at Johannes Gutenberg University Mainz in Germany, published the results of their evaluation of most of the statements, which they put through a computerized text-analysis program called the Linguistic Inquiry and Word Count. The biggest finding was a statistically significant difference between the average percentage of positive emotion words (9.64) and negative ones (2.65). Is that a lot?

To find out, the psychologists compared this data set with a broad spectrum of written sources, including scientific articles, novels, blogs and diaries, consisting of more than 168 million words composed by 23,173 people. The mean of 2.74 percent positive emotion words for each entry was statistically significantly lower than that of the prisoners. In fact, these death-row inmates were more positive than students asked to contemplate their own death and write down their thoughts and even more positive than people who attempted or completed suicides and left notes. What does this mean?

Hirschmüller and Egloff contend that their data support terror management theory (TMT), which asserts that the realization of our mortality leads to unconscious terror, and "an increased use of positive emotion words serves as a way to protect and defend against mortality salience of one's own contemplated death." But if that were so, then why the difference between the inmates' statements and those of suicide attempters and completers? Surely those about to kill themselves would be equally terrorized by the prospect of their imminent self-demise.

Context is key here. "Change the context slightly, and one often gets very different results in research on human behavior," University of California, Berkeley, psychologist Frank J. Sulloway told me by e-mail when I queried him about TMT. "The really tricky thing with theories like this is not what to do with statistical refutations but rather what to do with supposed statistical confirmations. This problem previously arose in connection with psychoanalysis, and [German-born psychologist] Hans Eysenck and others later wrote books showing that those zealous psychoanalytic devotees testing their psychoanalytic claims systematically failed to consider what other theories, besides the one researchers thought they were testing, would also be confirmed by the same evidence."

An alternative to TMT is one we might call emotional priority theory (EPT). Facing death focuses one's mind on the most important emotions in life, two of which are love and forgiveness. Love is an emotional feature of human nature so potent it can be tracked with neurochemical correlates such as oxytocin and dopamine. In fact, as Rutgers University anthropologist Helen Fisher argues in the revised edition of *Anatomy of Love* (W. W. Norton, 2016), love is so powerful an emotion it can be addictive, like chocolate and cocaine.

In this alternative context of EPT, I conducted my own content analysis of all 417 death-row final statements. I found that 44 percent either apologized for their crimes or asked for forgiveness from the families present at the execution and that 70 percent included effusive love language. For example:

- To my family, to my mom, I love you.
- I appreciate everybody for their love and support. You all keep strong, thank you for showing me love and teaching me how to love.
- I want to tell my sons I love them; I have always loved them.
- I would like to extend my love to my family members and my relatives for all of the love and support you have showed me.
- As the ocean always returns to itself, love always returns to itself.

Not only were these men not terrorized at the prospects of death, 40 percent of them said they were looking forward to the next life in expressions like "going home," "going to a better place" and "I'll be there waiting for you." TMT proponents counter that the terror is *unconscious,* revealed by expressions of positive emotions and afterlife beliefs. But is it not more prudent to presume that people say what they truly feel and believe in the seconds before their death and then prioritize those emotions and thoughts by what matters most? What would you say? SA

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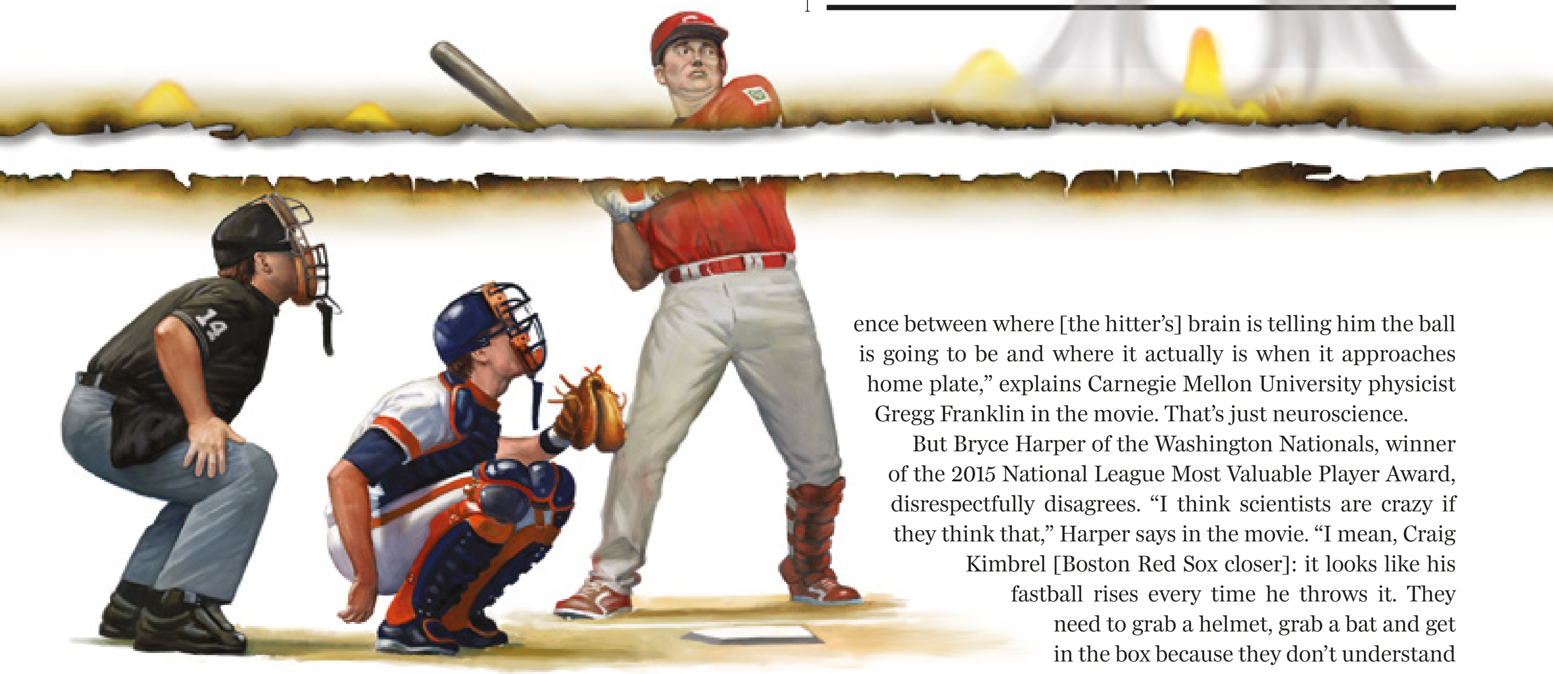
Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since cut-fastball master Mariano Rivera was still primarily a starting pitcher. He also hosts the *Scientific American* podcast Science Talk.



Arms Race

A movie about baseball's primary pitch is a hit

By Steve Mirsky

A baseball thrown by a top-flight power pitcher makes noise. "Oh, you can definitely hear a fastball," former Yankee Derek Jeter says in the excellent new documentary *Fastball*. "You can hear it whizzing by you. It sounds like trouble is what it sounds like. If you're facing someone with some control problems, it can be a very, very troubling experience."

I saw a preview of *Fastball* in March at the Yogi Berra Museum & Learning Center on the campus of Montclair State University in New Jersey. And the movie wasn't over even when it was over, because I bought a copy for repeated viewings. Baseball fans will obviously be fascinated by *Fastball*. But science aficionados will find a lot to like, too. If you love science *and* baseball, watching it will cause flights of angels to sing to thee. Possibly including Nolan Ryan, California Angel, 1972–1979.

The film examines everything from the physics governing the trajectory of the ball to the physiology of the strain on the pitcher's arm to the psychology of hurling a potentially deadly projectile awfully close to the head of another human being to the neuroscience of the batter's perception and reaction.

In the last area, many hitters swear that a really good fastball actually rises as it gets near them. Of course, the ball is still going down, because of gravity and air resistance, when delivered by any pitcher throwing overhand. That's just physics. The apparent rise compared with slightly slower pitches "is the difference between where [the hitter's] brain is telling him the ball is going to be and where it actually is when it approaches home plate," explains Carnegie Mellon University physicist Gregg Franklin in the movie. That's just neuroscience.

But Bryce Harper of the Washington Nationals, winner of the 2015 National League Most Valuable Player Award, disrespectfully disagrees. "I think scientists are crazy if they think that," Harper says in the movie. "I mean, Craig Kimbrel [Boston Red Sox closer]: it looks like his fastball rises every time he throws it. They need to grab a helmet, grab a bat and get in the box because they don't understand what's going on up there." If any scientist interviewed for *Fastball* responded along the lines of "Harper needs to grab a calculus text and get in a Newtonian physics class before telling us that *we* don't understand what's going on up there," it was left on the cutting-room floor.

As you'd expect, *Fastball* tries to determine who threw the fastest fastball. The zippiest pitch ever recorded by radar was thrown in 2010 by then Cincinnati Red and current New York Yankee Aroldis Chapman: 105.1 mph. The aforementioned Ryan, the all-time strikeout king (by a lot) with 5,714, became the first pitcher to have his fastball measured in an actual game by radar back in 1974. "The device was set up to measure his pitching speed about 10 feet in front of home plate," physicist Franklin explains. "And he was actually clocked at 100.8 miles per hour." Not in Chapman's league. Because it's probably better.

I did not know until I saw *Fastball* that in recent years pitch speed is measured 50 feet from home plate, "virtually the instant the ball leaves the pitcher's hand," says narrator Kevin Costner, who caught "Nuke" LaLoosh's high hard ones in *Bull Durham*. That's where Chapman hit 105.1. Franklin, based on calculations perhaps scarier to Harper than a pitch near his chin, estimates that when Ryan's 1974 pitch was 50 feet from home it was traveling at better than 108 mph. "So we believe that once we make corrections," Franklin says, "this is really the fastest pitch recorded."

I'm reminded of a story, probably apocryphal, as it's told as having happened with everyone from Ryan to the first renowned fastballer, Walter Johnson, on the mound. The pitcher throws a fastball with such velocity that neither the batter nor the umpire even sees it. But the ump calls it a ball. Because, he explains, it "sounded high." And, as Jeter would attest, like trouble. SA

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Illustration by Matt Collins

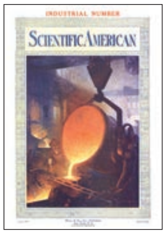
50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

JUNE

1966



1916

1866

1966 Health of a Nation

"What will be the effects on health of the increasing concentration of the population in cities and large urban aggregations? In spite of such known urban pressures on health as air and water pollution, water shortage, overcrowding, poor housing, the stresses of city transportation and the generally accelerated pace of city life, there is no substantial evidence from the National Health Survey that the overall health of the urban resident is worse than that of the rural resident. Indeed, the weight of the evidence indicates that the rural resident is at some disadvantage in terms of both general health and health facilities and services."

Structure of Enzymes

"For the first half of this century the metabolic and structural relations among the small molecules of the living cell were the principal concern of biochemists. The chemical reactions these molecules undergo have been studied intensively. Such reactions are specifically catalyzed by the large protein molecules called enzymes, many of which have now been purified and also studied. It is only within the past few years, however, that X-ray-diffraction techniques have made it possible to determine the molecular structure of such protein molecules. These giant molecules, which contain from a thousand to tens of thousands of atoms, constitute more than half of the dry weight of cells."

1916 Shackleton Rescue

"Credit is due to Shackleton for having brought back his men across the ice and sea to the South Shetlands and for having successfully reached South Georgia in a boat journey. Evidently a relief expedition will promptly be sent from the Falkland Islands or Argentina to rescue the main party, left on Elephant Island, and it is to be hoped that succor will reach these gallant men in time to prevent more suffering. I may venture to say that in the history of Antarctic exploration it would be difficult to find another example of an expedition having accomplished so little of the programme originally set forth. It seems evident that Shackleton counted too much on good luck and did not sufficiently take into consideration the possibility of adverse ice conditions. —Henryk Arctowski"

X-rays for Bullet Wounds

"To extract a bullet from the human body, it is necessary to know the location of the bullet very exactly. Dr. Wullyamoz, of Lausanne, has devised a method of reading this depth directly on a fluorescent screen. A Roentgen ray tube projects the shadow of a bullet upon a screen. If the tube is moved, the shadow of the bullet moves. The Roentgen ray tube, coil and accessories are mounted on a shelf attached beneath the operating table, and the surgeon keeps the bullet and the anatomical details continuously in view by means of a fluoroscope attached to his head [*see illustration*]."

More images of medical progress in 1916 are at www.ScientificAmerican.com/jun2016/medical

1916: Surgery performed with the help of x-rays.

SCIENTIFIC AMERICAN SUPPLEMENT, VOL. LXXXI, NO. 2110; JUNE 10, 1916

1866 Set Fire to the Sea

"The Boston *Commercial* says: 'The ship *S. T. Joseph,* recently arrived here from Liverpool, had a narrow escape on passage. It seems that among the cargo was a box marked sodium, which was placed on deck, with instructions to the effect that if there was any trouble with it from getting wet, to throw it overboard. Soon after getting to sea the captain took a dislike to this box. So he ordered a couple of old salts to pick it up carefully, and throw it over the stern. Instantly on its striking water a terrific explosion occurred, and an immense column of water was thrown up.' It is the nature of sodium to be very violent when thrown into water. Shippers who are aware of the risks will have nothing to do with it. One reason for the high price of sodium in this country is an extra charge to cover losses by shipment."

Odors of Disease

"The odor of small pox has been compared to the smell of a he-goat; that of measles to a fresh-plucked goose; scarlatina to cheese. The smell of plague has been compared with the odor of May flowers, and that of typhus with a Cossack. —Prof. Banks, *Medical Press and Circular*"

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Can You Read This from a Distance?

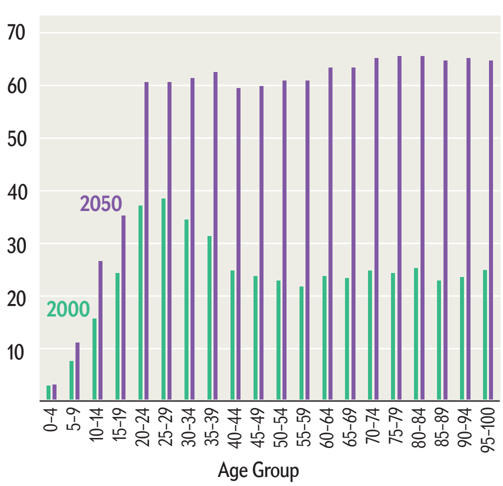
Nearsightedness is on the rise

The childhood insult "Four eyes!" may one day apply to most of us. By 2050, according to a new report from the Brien Holden Vision Institute in Australia, almost half the world will be nearsighted and require some form of corrective lens, up from a quarter of the global population in 2000. Conventional wisdom puts the blame for the rise in myopia on reading and staring at computer screens, but little evidence supports that hypothesis. Current thinking holds that people, especially children, spend too little time outside—a handful of studies show that lack of sunlight exposure from long periods indoors correlates with myopia.

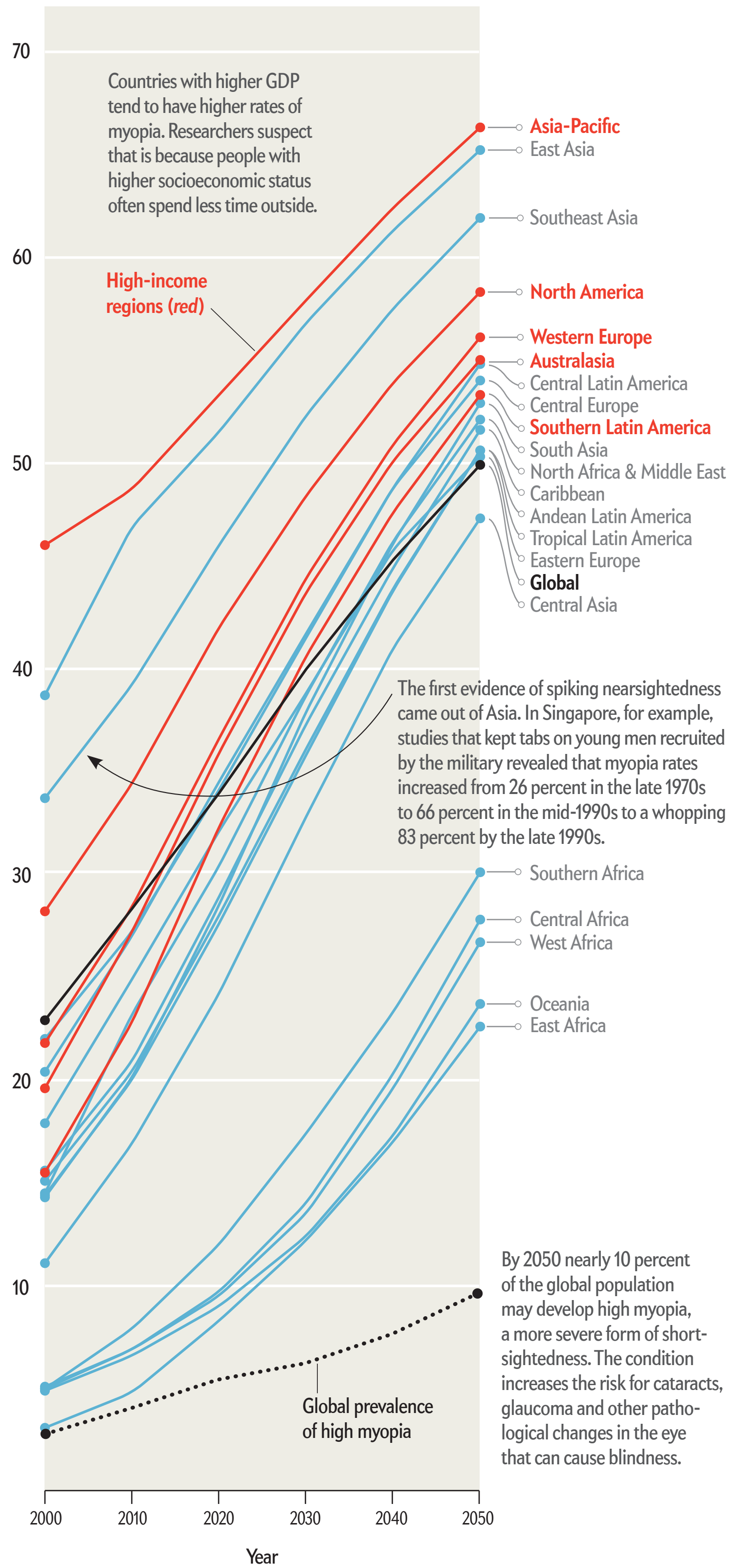
Either way, heredity clearly plays a smaller role than previously thought. "Myopia, once believed to be almost totally genetic, is in fact a socially determined disease," says Ian Morgan, an ophthalmology researcher at the Australian National University. The finding suggests an intervention: a recent trial revealed that children who spent an extra 40 minutes outside each day for three years were less likely to become myopic than those who did not.

—Diana Kwon

Pattern of Myopia Prevalence by Age Group Is Expected to Shift Dramatically by 2050 (percent of total)



Myopia Prevalence Is Projected to Continue Rising (percent of total population)



SOURCES: "GLOBAL PREVALENCE OF MYOPIA AND HIGH MYOPIA AND TEMPORAL TRENDS FROM 2000 THROUGH 2050," BY BRIEN A. HOLDEN ET AL., IN *OPHTHALMOLOGY* (IN PRESS) *(myopia prevalence)*; GLOBAL BURDEN OF DISEASES, INJURIES, AND RISK FACTORS STUDY, INSTITUTE FOR HEALTH METRICS AND EVALUATION *(classifications by high-income region)*

Graphic by Tiffany Farrant-Gonzalez